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14. ABSTRACT
The VPERC program at Hampton University was initiated with the goals of undertaking research into the most effective ways of producing spare parts for the Army's still-functioning legacy systems; developing means, methods and equipment to accomplish this production; and to actually produce complete and accurate technical data packages required to produce the parts. During this year, VPERC engineers actively promoted the capability of the Lab to evaluate, test and produce technical data packages for legacy parts actually needed at the Depot level.

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Report Title

Virtual Parts Engineering Research Center

ABSTRACT

The VPERC program at Hampton University was initiated with the goals of undertaking research into the most effective ways of producing spare parts for the Army's still-functioning legacy systems; developing means, methods and equipment to accomplish this production; and to actually produce complete and accurate technical data packages required to produce the parts. During this year, VPERC engineers actively promoted the capability of the Lab to evaluate, test and produce technical data packages for legacy parts actually needed at the Depot level. This was accomplished for several parts at three different Depot locations. So VPERC reached its potential during this year and moved on to broaden its capabilities to respond to a wider universe of types of parts by taking on those with more complex features and improving its analytical process and equipment for determining material properties of the parts. Much of the VPERC accomplishments are enhanced by Hampton's collaboration with Arizona State University and the University of Utah who contribute their unique skills in practice and theory to deriving an ever expanding response to the support of military legacy weapons systems.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Number of Papers published in peer-reviewed journals: 0.00

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Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

See Technical Reports from our collaboration partners, University of Utah and Arizona State University, posted on the ARO website.

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

(d) Manuscripts

Number of Manuscripts: 0.00

Patents Submitted

Patents Awarded

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Vadivel Jagasivamani	1.00	No
Eric Sheppard	0.00	No
FTE Equivalent:	**1.00**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
Amena Ross	0.20
Jennifer Edwards	0.20
Sybil Mackall	0.20
Courtney Golden	0.20
Ashley Nichols	0.20
Jasmine Butler	0.20
Linda Cornett	0.20
Shelitta Sheffield	0.20
FTE Equivalent:	**1.60**
Total Number:	**8**

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 1.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 1.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED	
Gerald Swenson	1.00	No
Detra Johnson	1.00	No
FTE Equivalent:	**2.00**	
Total Number:	**2**	

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Final Report to the Army Research Office
Scientific Progress and Accomplishments of the
Virtual Parts Engineering Research Center

Contents

1. Parts Requirements for the U.S. Army

1.1 History and Purpose of the VPERC Laboratory

Hampton University's Virtual Parts Engineering Research Center (VPERC) has been operational for seven years, commencing in April, 2001. The fundamental purpose of this effort is to conduct theoretical and practical research in deriving a solution to the Army's replacement parts procurement deficiencies for legacy weapons systems. The Center has made significant strides in addressing the many issues involved, in collaborating with other academic institutions and in imparting advanced knowledge and skills to both faculty and students.

The mission of the VPERC effort is to support the needs of the DOD in supplying the U.S. Warfighter with the right parts at the right place at the right time. This mission involves aspects of life-cycle management, lean manufacturing, outreach to industry, utilization of retrieved and theater provided equipment, and logistics. VPERC has developed the necessary infrastructure to characterize the material and physical properties of diverse parts and prepare 3-D CAD files for efficient production on CNC equipment.

1.2 Basis of the Legacy Systems Parts Procurement Dilemma

Legacy defense systems designed and manufactured decades ago are still serving the Army satisfactorily in warfare including service in the Middle East and Afghanistan. The reliability of these units is mostly dependent on proper maintenance and periodic replacement of worn and damaged parts. Obviously, the supply of spare parts in warfare is very critical, potentially causing immobility if not accomplished efficiently and hence, vulnerability for the soldiers unless the right tools and the right parts are delivered when they are needed. There have been cases in recent wars in which soldiers were required to improvise required parts from what was available locally or to make crude replicas; but even such compromised measures are not always possible and as a result, the solders are sometimes put in a disadvantageous and dangerous position.

These activities taking place at a time of armed conflict clearly identifies the need for a more progressive infrastructure and technology to perform rapid parts production with the capability to manufacture parts in small quantities and on demand.

Up to fifty years ago when some of the still-productive weapons systems were built, manufacturers did not routinely accumulate documents from all their subcontractors for subsequent inclusion in a comprehensive technical data package for delivery to the Army along with the manufactured units. Also,

most of the manufacturers did not store them for extended future use. Some manufacturers do not even exist anymore. And there are manufacturers who are not willing to share the information on manufacturing methods used, then or now. Consequently, when the originally supplied spare parts have been consumed, in many cases the Army has to resort to reverse engineering of parts so that valuable legacy systems can continue to serve the Army.

As a result of this lack of technical data, there is a strong demand for reverse engineering and reengineering initiatives to be carried out for the Army in order to supply ongoing parts. Many of the reverse engineering efforts currently are carried out on site, relying on the skill of the engineer and machinist who decide on the selection of materials and manufacturing processes based on past experience. These approaches have helped to meet the demand for parts to a degree; however, the VPERC Lab was developed to produce a scientific and systematic process dedicated to undertaking the reverse engineering process and producing technical data for parts production more reliably, rapidly, cost-effectively and professionally.

2. Approach to Parts Procurement for Legacy Systems

2.1. Traditional Process for Procurement of Parts

Traditionally, manufacturing data packages for parts and assemblies that are components of legacy weapons systems have been prepared as hard copyengineering drawings with accompanying printed specifications stored in paper form or on microfilm; drawings may also have been converted to C4 or pdf raster electronic format. Manufacturing from the raster drawing information requires consumption of a considerable amount of time and effort which are precious commodities when the manufacturing effort is directly supporting the troops in the field. Hampton University's VPERC Lab was conceived and developed to modernize the process of the procurement and manufacture of legacy parts to take advantage of the efficiencies and accuracies inherent in the contemporary digital, computer and web-based environment. VPERC engineers have identified the challenges to be overcome and have made great strides in developing a parts manufacturing process with Web-based interaction for rapid procurement of the parts, on-demand, with minimal human intervention.

2.2. VPERC Process for Parts Procurement

The VPERC process calls for the translation of legacy parts technical data into an electronic format either through redrawing of existing plans or through reverse engineering of the part where those plans are non-existent or inadequate for manufacturing. The electronic technical data is produced in a 3-D format—the VPERC Lab has chosen the ProEngineer application although there are other applications available—and translated into STEP-enabled format for direct insertion into the appropriate manufacturing equipment. STEP is an acronym for Standard for Exchange of Product Model Data. The part's technical data as well as the manufacturing processes are Computer Numerically Coded (CNC) then manufactured directly from the electronic data.

VPERC technology uses the Internet for communication between different groups involved in the manufacturing process, as shown in figure 1. Once the part is captured in CAD and exported as a STEP file into a designated repository, the system is designed to permit acquisition of a given part's technical data in an expeditious fashion.

The end-user of the part may identify his needs by searching for the part through the Internet. Once identified, the user can then contact approved manufacturers for quotations and delivery schedules and the order for manufacturing can be awarded. All these are possible over the Internet without other, more time-consuming interventions. Since the data package is maintained in the repository in a form most

appropriate for rapid manufacturing, the process provides a platform for faster acquisition of the part for end-users.

Manufacturing data on parts (including drawings and specifications) are committed to the central repository only after several quality checks and are therefore are predominantly free of errors. And since the data are virtually error free, the VPERC process results in the production of parts with fewer rejections during manufacture, less time for parts completion and delivery, and economy in procurement. Since the data files have been stored electronically, process planning and CNC programming will be more expeditiously accomplished and will result in reduced data input errors. This process is most appropriate for production of parts in small quantities, since the relative savings on process planning and CNC coding are greater using STEP (AP224) files. Furthermore, globalization in manufacturing is made more efficient through Internet distribution.

2.3. Standardization of Data Format for Parts Procurement

There are several CAD vendors in the industry with products that export CAD data in proprietary formats which cannot be interpreted by the users of other CAD packages. This makes it very difficult to exchange data among users of the different software. Furthermore, the process of converting formats or translating may not reveal all the features of a given part correctly.

The globalization of manufacturing is expanding rapidly and there is a need for an international standard for representing product data. The International Standards Organization (ISO) and American National Standards Institute (ANSI) are promoting STEP application protocols as a way to standardize the representation of product data models. Currently most of the popular CAD packages have the capability of importing and exporting some of the STEP application protocols, paving the way to the standardization of product model data through STEP and also reducing the burden of reworking CAD models when CAD systems or data processing systems change.

CNC machines for parts manufacture have been used for the past forty years in industry. These machines need machining instructions programmed in appropriate CNC codes. Currently STEP technician-users are encouraging the development of STEP-NC machines which take STEP files more readily and thereby reduce the cost of programming for each manufacturing activity. All these efforts help introduce “lean” manufacturing efforts into the industry and particularly in producing legacy parts for Army systems efficiently and economically.

2.4. Remanufacturing Parts for Legacy Systems

The remanufacturing of parts for legacy systems falls into three major categories: reverse engineering, reengineering and redesign. When it is required to add functionality to an existing part, the process of redesign can provide added features, more appropriate materials and/or enhanced manufacturing processes. If the part is found to fail too often, then the process of reengineering can be carried out to improve the reliability and life of the part. Similarly, if the materials and processes that originally went into the development of the part are inappropriate for todays manufacturing techniques, reengineering the part will permit the application of appropriate processes and materials.

2.5. Reverse Engineering Process

Parts that are required to be duplicated without any change in features or functionality are subjected to reverse engineering. The process is almost the same as with the original part's development, namely: understanding the functionality associated with the part and with other interacting parts in an assembly, deducing the geometry and dimensions, identifying the materials, processes and manufacturing processes, developing quality assurance methods, and determining the necessary maintenance procedures.

The tasks involved in the VPERC reverse engineering process will generally include the following, depending upon the characteristics of the part (see figure 2):

1. Identify the functions
2. Identify each component in an assembly
3. Perform failure analyses to prevent future failures
4. Check for availability of ready-made pieces (bearings / shafts/ gears / fasteners)
5. Evaluate fabrication methods
6. Select materials
7. Identify treatments
8. Identify testing/evaluating methods
9. Establish maintenance and test procedures
10. Identify potential manufacturers

The actual process and methods of reverse engineering will be determined by such factors as the quantity of parts required, cost of manufacture, time constraints to complete the process and determination of whether the part is used in sensitive or critical applications. Figure 3 shows the infra-

structure as it has been developed at VPERC to carry out reverse engineering and failure analysis in a systematic manner. Capabilities and facilities are continually being updated based upon the needs of eachprogram.

2.5.1. Mechanical Measurement

Dimensional data on simple parts can be measured using calipers and gauges; however, a computer measuring machine (CMM) or similar complex equipment will be required when the geometry and details become more intricate. The VPERC reverse engineering process efficiently collects this data and presents it in an electronic data package to be used by manufacturers.

2.5.1.1 Computer Measuring Machines

Computer measuring machines and other metrology equipment can be used by skilled personnel to acquire accurate dimensional data. All of the relative dimensional data necessary for the creation of an exact CAD replica of the component can be obtained. When the geometry is simple this is probably the best method for deducing the mechanical dimensions. The dimensional data thus obtained is analyzed and nominal values are formulated, taking into consideration the component's function, associability, manufacturing processes, industry standards and customer specifications. Finally the data is used to prepare the CAD models. A 3-D model can be generated using one of several compatible CAD packages.

2.5.1.2 Laser Scanning

Laser scanning is used very commonly where the geometry of the part is too complex to handle with mechanical measurements or when the part is too large to handle with conventional methods. The part can be partially or fully scanned using laser scanning equipment. Separate partial scans are aligned and merged into a single surface made of thousands or millions of triangles in a large mesh. Places that are obscured from the scanner and may be filled in manually. Once the polygon surface is watertight and cleaned up, a NURBS surface is generated. NURBS (non-uniform rational B-spline) surfaces can be modified in limited fashion by 3-D CAD packages or can be exported directly to IGES or other formats for machining or molding.

2.5.1.3 Optical and Other Methods

Optical instruments are used to determine the shape and size of a part and identify some critical features. The instrument used on a given task may range from a simple measuring microscope to dedicated optical instrumentation for use in metrology. When the geometry of the part becomes more

complicated, it is preferable to have more than one technique available to deduce the geometry and dimensions so that the most appropriate one can be adapted to suit the situation.

2.5.1.4 Applications of Ultrasonics in Reverse Engineering

Ultrasonic instrumentation is widely used in nondestructive testing and in materials research. It is successfully used in the measurement of thickness of materials with access from just one side of the object. For the most part, ultrasonic methods of testing rely on the acoustic and elastic properties of the materials. With some basic understanding of the principles and techniques of testing, ultrasonic methods can provide data on mechanical measurements that would not be otherwise available.

Hampton's VPERC Lab has developed a technique to acquire the geometry and the dimensions from parts using an ultrasonic scanner (figures 4 through 7). The part is subjected to C-scan, wherein an ultrasonic probe executes an X-Y raster scan on the part with the part immersed in water. During the scan the instrument collects A-scan data. Depending on the presence of features in the part at different depths, gates are set to extract reflection data from the A-scan and the C-scan image is built. C-scan images are collected at different depths from a given part. All the data are collected in a single scan. Such plots provide both geometrical and dimensional data to use in developing a 3D model. The process is also useful in collecting data from regions of the part that cannot be accessed by conventional mechanical tools. Ultrasonic testing can identify the structure of the part and materials; and an ultrasonic method of evaluating surface finish of machined surfaces has been developed to automatically identify the orientation and roughness of machined marks.

2.5.1.5 Fused Deposition Modeling Unit (FDM)

The VPERC Lab's Fused Deposition Modeling unit provides it with the capability to carry out rapid prototype development (figure 8). The unit is also useful in fabricating fixtures, templates and patterns out of ABS plastic. The FDM unit accepts STL files exported from 3D CAD models and generates the object in a few hours. This capability helps visualize 3D objects after the part is conceived. Senior engineering students have made use of the unit extensively in fabricating fixtures and housings required to carry out their engineering design projects. Another area which will be tested is the suitability of the unit in making patterns that will be used in manufacturing castings.

2.5.2. Materials Identification

Military weapons system parts are manufactured in a very broad range of materials. Some of the high-technology parts use special materials which cannot just be replaced with commonly used engineering

materials. High strength alloys, composites (polymer composites and metallic composites), and the like cannot merely be replaced by more common materials, unless required modifications are instituted in the overall design. Also, some materials may need suitable heat-treatment to bring out optimal properties.

If the information on the material used is not available, it is essential to introduce systematic material analyses to be able to arrive at informed decisions. When a part fails prematurely it is essential to learn about the cause of failure and apply necessary modifications into the design. End-users' feedback to the extent that it is available should be given due consideration as a factor in deriving appropriate changes in the design and/or materials of manufacture.

2.5.2.1. Emission Spectroscopy Studies

Optical emission spectroscopy is commonly used to identify the composition of the material. The process involves striking an arc on the material and studying the characteristics of the emission spectrum. The process needs very little preparation on the part of the sample, and the process provides quick results with an acceptable degree of reliability.

2.5.2.2. Metallography and EDX Studies

Metallography is conducted to identify the type of material, approximate composition and the kind of heat-treatment exhibited by the sample. It is carried out either by an optical microscope or by using an electron microscope. Energy dispersive X-ray analysis (EDX) is attached to scanning electron microscopes and transmission electron microscopes. EDX studies identify the distribution of different elements in different grains of the sample.

2.5.2.3. X-ray Diffraction Studies

Parts selected for reverse engineering that have been subjected to severe working conditions aresubjected to metallographic and X-ray diffraction studies to identify the materials, manufacturing methods, heat-treatment and residual stresses in the part (figure 10). These studies provide the necessary data to propose more appropriate manufacturing methods to be used while remanufacturing.

2.5.2.4. Special Techniques

A number of special scientific instruments and processes play a key role in the effective reverse engineering of parts: micro-probe analysis, X-ray fluoroscopy, ultrasonic instruments, eddy current units are a few of the tools/processes which may be required in complex cases. The optimum tool to be used will depend on the nature of the part to be studied.

2.5.2.5 Selection of Materials

In reverse engineering the materials used in the original part are specified to the extent possible. However, there are other considerations such as cost, safety issues, recyclability, toxicity and manufacturability that will guide in the selection of more appropriate materials for remanufacturing.

During the past fifty years constant change and improvement in materials has been an industrial standard. Composites, ceramics, smart materials, shape memory alloys, super plastic materials and nano-structured materials may be more appropriate substitutes in a reverse engineered part. Also, materials that are more receptive to nondestructive testing are preferred to enable periodic quality assurance testing.

Conversely, toxicity in materials in the recent times has discouraged the use of materials such as lead, cadmium, mercury, beryllium, etc. Also, it is advisable to avoid the use of dissimilar materials in an assembly to reduce corrosion problems as well as materials which pose problems during manufacturing or welding that may give rise to severe heat affected zones or embrittlement.

2.5.3. Manufacturing Processes

The performance of a part depends in large part on its method of manufacture. Forming methods such as forging or rolling generally provide superior performance. Casting methods are highly useful in achieving complex shapes with rigidity. Machining methods provide higher dimensional accuracy. Sometimes welding or metal joining methods are specified to develop parts with complex shapes. Apart from these conventional methods of manufacturing, adhesive bonding, powder metallurgy, nano-structured powder metallurgy and high velocity forming are becoming more popular for special applications. It is necessary to identify the most appropriate method for each particular part.

2.5.4. Treatment Processes

Heat treatment and mechanical treatment are applied to finished products to improve the performance of the part in wear resistance, durability and strength. The effectiveness of heat-treatment can be verified by conducting detailed metallographic studies or by simple hardness measurement (figure 9). In many cases, it is appropriate to conduct the measurement of hardness on the finished product, to ensure that the part has undergone proper treatments.

2.5.5. Coating Processes

Coatings provide corrosion resistance, wear resistance, specific frictional characteristics, specific optical properties, thermal characteristics or more appealing appearance. The type of coating and the process to be adopted are critical to achieve the desired properties and functionality.

2.5.6. Quality Assurance Methods and Developing Maintenance Procedures.

Quality assurance and nondestructive testing are useful to ensure the quality of the product. Nondestructive testing is widely used in critical parts, so design of the parts, whether new or remanufactured, should consider and allow for easy physical access to nondestructive testing points.

Parts placed in service after reverse engineering should be periodically inspected to avoid catastrophic failure during service. The reverse engineering task should consider this aspect and advise methods of inspection at appropriate intervals as a component of the part's technical data package.

In addition, VPERC is taking a proactive approach to QA by investigating the potential for developing "smart parts" that can detect abnormalities while they are in use; also, our engineers are using modeling and simulation techniques to detect potential weaknesses in parts and materials. These activities are discussed more fully in paragraphs 3.3 and 3.4 to follow.

2.6. VPERC's approach to meeting emergency needs

The engineers of VPERC recognize that system breakdowns occur in the field and call for immediate resolution to prevent operations from being compromised. This is a situation VPERC does not address even though VPERC is dedicated, at least partially, to rapid parts replacement. It calls for a technique, a facility, a means of providing parts replacements on an *ad hoc* basis on-site, as close to the system as possible. VPERC engineers have adopted a tasking to identify parts that would commonly fail and to develop field-adjustable replacement solutions. An example of this type of part is a power transmission rod used where there is a need to link a power source to a power user, one which can be quickly assembled from several smaller interchangeable parts. Development of this adaptable part was the primary focus of a study undertaken by Hampton amd its VPERC collaborators, Arizona State University and the University of Utah. Graphic demonstrations of the various approaches to this investigation are provided in figures 14-21 of this report.

3. Current R & D Activities

3.1 Reverse Engineering Efforts for the Defense Agencies

Parts Manufacturing for the Defense Logistics Agency (DLA)

Parts development and reverse engineering officials from the Defense Supply Center, Columbus, Ohio have visited the VPERC Lab to evaluate the facility and deliver a set of parts to be reverse engineered and have technical data packages developed for them. The parts conveyed thus far consist of a large shackle, a swivel & link assembly, and an air filtration housing. The VPERC staff has responded to the needs of Defense Supply Center (DSC), Columbus and carried out systematic analyses to arrive at optimum materials and manufacturing methods as defined in newly-produced contemporary technical data packages.

A photograph of the shackle referenced above is shown in Figure 23. A piece of metal was cut from the shackle for metallographic studies under the scanning electron microscope in order to identify material, structure, heat treatment and coating thickness. The microstructure indicates defragmented grains and cracks along the outer surface owing to the forging operations, as shown in the figure 11. Also a small piece was subjected to X-ray diffraction to study the composition. CAD modeling was produced for the part and manufacturing instructions were prepared to provide a comprehensive guide to the part's development on contemporary machining equipment.

Also, Hampton University has received C4 drawings and photographs of parts for reverse engineering from the Defense Supply Center, Richmond, VA and CAD modeling has been undertaken. We have held discussions with parts managers at the DSC site in Richmond and parts for manufacture have been identified from the agency's web site. We have reached agreement with DSC Richmond for them to ship parts to HU to incorporate into the VPERC process.

3.2 Review of Alternative Manufacturing Processes

There are several manufacturing methods, such as forging or pressure die casting that are not commonly found in routine manufacture but are found in the development of legacy parts. Although these methods may be appropriate for production of parts in large quantities, they are less suitable for redevelopment of legacy parts since the qualities of legacy parts are generally much smaller and the manufacturing preparation is out of proportion to the required results. Furthermore, legacy parts may heve been manufactured using materials which are typically no longer used in manufacturing or have been superseded with improved materials. Engineers and students at the VPERC Lab are attempting to

resolve these conflicts through reverse engineering and reengineering to produce equivalent or improved legacy parts replacements. A review of several manufacturing methods and their applications in parts productions in small quantities were presented in the 2006 VPERC annual meeting held at Durham, North Carolina and the most recent annual meeting held at the campus of Hampton University early this year.

A 200 W radio frequency induction power system is being developed at Hampton University to explore the application of power RF systems in developing nanostructured fabrication methods and in the treatment of parts.

3.3. Development of Smart Parts

Parts used in some critical assemblies can incorporate sensors to intelligently interpret the integrity of the part and service conditions; such information can be transmitted outside of the confines of the system to provide data to improve the safety and the reliability of the whole system. A load bearing member mounted with transducers is being developed to monitor service conditions and to detect any abnormality in working conditions encountered by the part.

3.4 Modeling and Simulation of Stresses

Parts which have failed during service have been identified and studies on structural and thermal stresses on the parts have been carried out to analyze the mechanical stresses and the thermal gradients during service. Using the ProEngineer application, VPERC engineers are able to model each part and analyze it as a complete part when only a broken or severely worn part may be available, to monitor that part’s behavior in a variety of contexts and environments and to subject the part to simulated stresses. In addition, the modeling platform allows the engineer to test the use of alternative materials or methods of manufacture.

As an example, one of the parts developed for the DLA’s Richmond center was an airspeed indicator gauge casing from a T-38 aircraft which had a broken mounting flange. This part was modeled as a whole piece, a technical data package generated, and the replacement part was produced using alternative contemporary materials. See figure 12 in this report.

3.5. Adhesive Bond Nondestructive Evaluation

Adhesive bonding is used as a contemporary fabrication method. One of the major difficulties in using adhesive bonding is the inconsistencies in assessing the integrity of the bond. Severe changes in ambient temperature and stresses, for example, can cause early deterioration. Studies are currently being carried out to develop techniques of nondestructively assessing the integrity of a part using ultrasonics.

Researchers are working on developing the technique by characterizing the reflected sound waves from the bond-line region. At Hampton we carried out studies to monitor in-situ temperature and acoustic properties as the dynamic loads are applied to the bonded region.

Measurement of acoustic properties of parts under the influence of external dynamic stresses was carried out in the VPERC Lab in order to understand the behavior of the adhesive layers to stresses. A non-intrusive copper resistance thermometer was embedded in an adhesive layer to monitor the dynamic temperature change with the applied static and dynamic loading. Static loading causes transient effects on acoustic properties. During static loading the adhesive layer is subjected to stresses and relaxation. Relaxation causes an increase in temperature for a short time. The effectiveness of the static stress on the bondline depends on whether the bondline sustains shear stress, a characteristic that is a factor of the quality of adherence. In this way, the measurement of transient effects of stresses on adhesive properties is expected to reveal the integrity of the bond. With dynamic loading, an increase in temperature of the adhesive layer was realized, resulting in reduced elasticity and reduced velocity of sound. It was observed that the influence of dynamic load on the properties of a bond layer is greater in a good bond because stresses in the bondline are sustained in a good bond, as shown in figure 13. These test results were presented at the ANST conference held in St. Louis, MO on June 6-7, 2008.

3.6. Erosion and Wear Studies

Military units operating in dusty environments like the Middle East may be subjected to severe operating conditions, exemplified when moving parts encounter abrasive sand blasts. Currently, our engineering students are pursuing studies related to wear and erosion from abrasive sand particles around and within bearing assemblies. The ongoing work will involve studies on the dynamics of abrasives in the bearing regions and deriving methods to mitigate damage.

3.7. Academic Collaboration on VPERC

Hampton University has maintained a collaborative relationship with the University of Utah and Arizona State University since the early days of the VPERC program’s commencement. Specifically, the collaboration is between Hampton’s VPERC Lab and the University of Utah’s School of Computing, Geometric Design and Computation Research Group, along with Arizona State University’s Design Automation Lab. Utah’s effort is being directed by Dr. Rich Riesenfeld, Dr. Elaine Cohen, and Dr. Sam Drake; Arizona State’s contribution is under the direction of Dr. Jami Shah.

Each institution involved in this effort provides a unique package of academic skill sets, scientific direction, interest, equipment and facilities, and experiential knowledge in the subject matter of legacy systems spare parts development. Each party contributes to the overall body of knowledge according to their interests and their capabilities. While continually elevating the plane of knowledge and application, each institution pursues its particular research targets with a knowledge of the activities, interests and intentions of the sister institutions, shaping their own activities to be cooperative and supportive and directed toward the overall goal of developing a more complete manufacturing process for the most complex of legacy system parts. Toward that end, at the highest academic levels, each university contributes in the following ways:

Hampton University. Hampton's contribution is through the development of a comprehensive technical dataset on each of the parts under study. Each dataset consists of technical specifications and drawings that are rendered in STEPTrans, an application developed by South Carolina Research Authority, to export the data in ISO10303 STEP AP224 format; this promotes ISO-STEP, reducing the efforts for process planning and CNC programming. Hampton identifies the optimum manufacturing processes and materials suitable for remanufacture of the parts for legacy systems; this is accomplished with the help of the sophisticated materials and mechanical testing facilities at the VPERC Lab. Hampton promotes ISO-STEP and CAD data that is provided in an electronic format ready for processing in STEP-enabled systems. This process keeps errors in CNC programming to a minimum, a required capability where parts in small quantities are being remanufactured.

University of Utah. Utah addresses 3D scanning issues, geometric issues, tool path optimization, machining issues and developing haptic systems and virtual reality interfaces to handle geometry issues. The university also is equipped with a laser scanning facility, CNC machining facilities, and EDM capabilities. For many reasons, technical and systemic, geometry may not be able to be altered, so Utah concentrates on extending the knowledge and capability of NC manufacturing to be supportive of this activity. Legacy parts development in general calls for the use of NC technology on designs that would be rejected today as too aloof to manufacturing issues using today's technology. Unfortunately, we are often caught with a "frozen" shape that must meet legacy specifications, so Utah determines how to extend manufacturing techniques to be more effective in handling such legacy problems. In particular, Utah addresses the challenging task of exploring the automation possibilities for machining situations and develops optimum algorithms to deduce tool path.

Arizona State University. In the development of the CAD to CAM process, one important task has been to interpret machining features to carry out process planning. ASU has developed techniques to

identify features, geometry, dimensions, tolerances and optimum materials; and they have the expertise in identifying features from differing CAD data so that optimum process planning can be deduced. ASU has developed techniques for using design intent to evolve redesign of parts, extracting geometry of parts, determining interfacing constraints, and other critical skills which are appropriate in developing techniques for reverse engineering parts for legacy systems.

3.8. Collaborative Efforts in the past few years

3.8.1 Gearbox reengineering

A collaborative project to reengineer a legacy gearbox was undertaken by the team to test out the processes of remanufacturing. This gearbox was originally used in the Newport News (Virginia) Shipyard and was provided by Northrop Grumman Newport News for the purpose of research.

At Hampton University, CAD data was developed for the gearbox with suggested tolerances, materials, and manufacturing processes to be employed in remanufacturing. Geometry and dimensions were deduced by conventional methods of manually handling each part.

Arizona State's Design Automation Lab performed redesign using a knowledge base and developed CAD models and bill of materials for the complete assembly.

The University Utah carried out laser scanning of the overall casting to deduce the geometry. The assembly was dismantled and each part was machined at Utah's sophisticated in-house CNC-enabled manufacturing facilities. The outer case was redesigned by Utah to suit their machining infrastructure. Gearbox components were put together to form a complete unit, thus demonstrating the possibility of carrying out complete reverse engineering or reengineering tasks.

A summary of the gearbox engineering effort was published in *Mechanical Engineering Design*'s February 2004 issue.

3.8.2. Feature Recognition

With the support of Hampton University, ASU developed a machining feature recognition system for extracting features from CAD files and generating STEP AP-224 files. The parts' geometry files prepared by Hampton University were interpreted by the software module developed by ASU to extract features and prepare STEP AP224 files. A report, "Feature Recognition & Data Exchange: A Joint

Project of ASU and Hampton U., Sponsored by ARO/VPERC" was presented describing the possibilities of interpreting and exporting features which could be valuable in the process planning efforts.

3.8.3. Reverse Engineering for the Defense Supply Centers in Richmond and Columbus

As described elsewhere in this report, the VPERC team has carried out reverse engineering efforts on parts supplied by the Defense Supply Center, DLA, Richmond (VA.) and Defense Supply Center, Columbus, Ohio. This cooperative effort provides VPERC with an opportunity to develop improved remanufacturing techniques while it serves the DLA in that agency's parts procurement efforts. The first part undertaken for DSC Richmond was a housing for an air-speed indicator gauge on the T38 aircraft as described elsewhere in this report. The reverse engineering and manufacturing effort was carried by all three collaborating universities. This housing was broken at one of four mounting flanges. Hampton and the University of Utah were charged with reverse engineering the case and manufacturing a replacement part as close to the original as possible. Hampton provided the technical data package which gave the necessary information in the proper format to manufacture the part using CNC equipment. Utah, with its state-of-the-art CNC manufacturing facilities produced the part using various materials and various processes. Focus: HOPE, one of a number of capable manufacturing partners of VPERC, machined the same part using our CAD data. This housing, along with the technical data package, was submitted to DLA, Richmond and was approved for manufacturing.

3.8.4. Development of a Rapid Re-Engineering System and OAM+

The three universities also collaborated on a research project on rapid re-engineering efforts. The resulting report explored the possibilities of developing an engineering part by a variety of different methods. The effort is based on extracting the part features from the CAD assembly model.

The part proposed for redesign under this collaboration is a linking component. It is a completely made-up part that allows us to introduce complexities and functional challenges which may not be completely available in a real part. It has spherical surfaces of some complexity, and it has both turned and milled features. Its intended function is to transfer torque via rotational motion. It mates with other parts at each end with pin joints, so it must satisfy some kinematic constraints, i.e. it allows one rotational degree of freedom with respect to its hole part feature co-ordinate.

Graphics of the link assembly are shown in figures 14 and 15. The link serves as the connection between a motor drive and a load and is designed to alleviate axial alignment issues.

Each of the different possible design approaches would not have a negative effect upon the design intent of the part. Each design was studied for stress distribution with a factor of safety of 1.8. In this way, four possible designs have been evolved. Some of the design approaches will yield rapid reproduction of the parts. The parts have been subsequently manufactured at the University of Utah and are being subjected to evaluation at Hampton University. A paper has been presented at ASME 2007 International Design Engineering Conferences, entitled "OAM+: An Assembly Data Model for Legacy Systems Engineering".

3.9. Current Collaborative Efforts

3.9.1. Replacement parts for emergency use in warfare

The US military still successfully employs several legacy systems in the battlespace. But, in order to use these systems consistently and productively, spare parts need to be available readily as and when need arises. For many reasons, it is difficult to maintain a supply of a wide variety of parts at remote locations. VPERC has identified some of the commonly used structural parts and identified the possibilities of quick replacement of such parts to keep a given system in service. A transmission link, one of the products of our university collaboration, has been identified as one such part, commonly used in drive systems (figures 16a, 16b). The transmission rod, along with coupling links, was studied for load and kinematic relations to predict the useful /dependable life of such parts that are subjected to fatigue loading during service.

Transmission rod

Test samples are currently being studied for their kinematics and structural integrity, including fatigue strength. Subsequently the test samples will be subjected to real fatigue loading to test agreement among the analytical predictions and experimental test results.

Three test programs for 1020 steel were planned as follows (figure 17):

- Test Program 1:
  - Torque varies sinusoidally between 0 and 6 Nm (0 to 53.1 in-lbf) at 0.2 Hz (17280 cycles per day, 120.96 k cycles per week)
- Test Program 2:
  - Torque varies sinusoidally between 0 and 3 Nm (0 to 26.55 in-lbf) at 0.2 Hz (17280 cycles per day, 120.96 k cycles per week)
- Test Program 3:

Torque varies sinusoidally between 0 and 1.5 Nm (0 to 13.275 in-lbf) at 0.2 Hz (17280 cycles per day, 120.96 k cycles per week)

Structural analysis

Three test programs were proposed for the transmission rod of 1020 steel, subjected to three different peak levels of torque, namely 6 Nm, 3 Nm and 1.5 Nm. The assembly model of the drive components working together is shown in figure 18. There is no stress concentration because of the large radius at the end and therefore no notch factor, K_f need be used. Since this is a case of pure torsion the von Mises stress will be √3*max shear stress. The maximum shear stress and von Mises equivalent stresses were analyzed from FEA (figure 19, 20 and 21) are presented in this table:

Test	Peak torque	Max. Shear stress (kN)	Max. von Mises (kN)
1	6 Nm	93	167.7
2	3 Nm	46.5	83.6
3	1.5 Nm	23.2	40.03

Failure analysis: Fatigue

Several factors affect fatigue strength. These include: the type of load, size of the specimen, surface finish and stress concentration. Endurance limits and SN curves are typically obtained from standard 6 mm round specimens with polished surfaces. The load used is reversed bending. Results are reported typically for a 50% probability of failure.

In our case study it is assumed that the surfaces are ground and not polished. The specimen is less than 6 mm; therefore, no size correction factor is needed. However, the load is torsional mode and not reversed bending. A shear correction factor (ks) of 0.577 needs to be applied to reduce the endurance limit. For reliabilities higher than 50% we also need to apply another correction (kR). We decided to conduct our exercise for three reliability values: 50%, 90% and 95%.

The empirical S-N-P curve is given by the equation:

$$S_N = 10^c N^b$$

The correction factors and empirical constants have been calculated for three reliabilities. This modified SNP will be used in the failure prediction.

Case	Max. von Mises (ksi)	Mean von Mises (ksi)	S_N (ksi)	50% Reliability life	90% Reliability life	95% Reliability life
1	35.63	17.82	24.5	36 334	29 216	27 492
2	17.82	8.91	10.31	Infinite	821 649	728 057
3	8.90	4.45	4.78	Infinite	Infinite	Infinite

There will be no fatigue failure for load level 3. Level 2 is also close to infinite life but it is predicted that up to 10% will fail before reaching 821,000 cycles and 5% of the samples will fail before reaching 728,000 cycles. The maximum load level is in case 1where 50% of the samples will fail before reaching 36,300 cycles.

The experimental configuration for carrying out the evaluation of fatigue strength using test samples is shown in figure 22. This test configuration, along with instrumentation and data acquisition systems, is being developed at Hampton University to carry out the experiments and compare with analytical results.

3.10. Additional reverse engineering work undertaken for defense agencies

VPERC has carried out reverse engineering tasks on actual required replacement parts for defense agencies such as the Defense Supply Center, Columbus, OH, Tobyhanna (PA) Army Depot and DSC Richmond, VA.

DLA, Columbus, OH

Three parts (figures 23, 24, 25 and 26) were subjected to reverse engineering, a shackle, swivel and hook, and air filter assembly. CAD models of the parts were prepared using ProEngineer. Drawing standards, title blocks and methods of collecting and reporting mechanical data were carried out according the procedures specified by DSC officials. The 2D drawings were exported as dxf files to meet the needs of the Center. Complete reverse engineering report and technical data packages were prepared detailing the methods adopted and reasoning used in deriving mechanical, metallurgical and manufacturing data.

US Army, Engineering Division, Tobyhanna, PA

Similar efforts were undertaken in preparing a technical data package for Tobyhanna Army Depot on an antenna mount assembly, mounted on wheeled vehicles (figure. 27).

DLA, Richmond, VA

A duct-coupling provided by the DSC, Richmond was subjected to reverse engineering. Figure 28 shows the 3D model of the part. The part is currently being tested for deducing the composition of the material and the nature of a small peripheral weld and potential alternatives.

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4. Summary of Technical Progress

The VPERC program at Hampton University has established a significant academic and applied base in the multiple efforts required for effective parts procurement for legacy weapons systems. We have undertaken studies and produced results on alternative methods of manufacturing parts that are most effectively suited for legacy systems. In addition, our collaborative efforts with the University of Utah and Arizona State University have provided our institution, including faculty and students, with insights into high level research and alternative approaches. The VPERC program has also provided Hampton with the capability of developing a fully functional research laboratory suite that is dedicated to the remanufacturing of complex parts of legacy weapons systems. The research and testing facilities created by the VPERC program also allow Hampton University to carry out multi-disciplinary research in such other high-level fields as the development of catalysts, alternative energy development activities, development of optical materials, development of techniques to improve the reliability of bridges and other relevant fields of study.

Hampton University is poised to produce an ever-higher level of both academic investigation and practical implementation in the disciplines involved in legacy system parts reengineering. Our goal remains to derive solutions to the challenges involved in supporting the ongoing operational use of aging but effective weapon systems, and to respond positively to these challenges with the research needed to improve these solutions. Our overriding goal is to continue to provide optimal support to the warfighter in the field.

5. Proposed Future Efforts

5.1. Parts procurement services to US defense agencies

5.1.1. Expanding services to the defense agencies

VPERC will continue to undertake reverse engineering tasks for the armed services through their logistics agencies, especially on parts that are neglected by commercial reverse engineering entities. Some of the reverse engineering tasks may involve development of alternative approaches in terms of materials, processes and functionalities. Also, in the case of remanufacturing critical parts, where reliability is of great importance VPERC will look to refine the techniques of incorporating testing probes within the parts and assemblies for in-situ monitoring.

5.1.2. Maintaining a database on TDPs for defense parts

Developing and maintaining a comprehensive, reliable database of manufacturing details on parts that are commonly required for the warfighter will help the Army procure parts quickly. VPERC has at its core the implementation of this approach and will continue to implement it as an effective method of serving the defense community by providing parts in an efficient and economical manner, when and where they are needed.

5.1.3. Identifying optimum theater-based replacements of parts in an emergency.

The US military still successfully employs several legacy systems in the battlespace. But, in order to use these systems consistently and productively, spare parts need to be available readily as and when need arises. For many reasons, it is difficult to maintain a supply of a wide variety of parts at remote locations. VPERC has identified some of the commonly used structural parts and identified the possibilities of quick replacement of such parts to keep a given system in service. To the extent possible, this will continue to be a collaborative effort with ASU and Utah, thus drawing upon the skills and specialties of each of the schools in supporting the warfighter.

5.2. Developing newer methods of manufacturing

Hampton will continue the search for newer methods of manufacturing, materials and techniques, promoting quality assurance in remanufacturing parts for the Army. This will include fundamental studies to develop newer materials (including nano-structured materials) and embedded sensors.

5.3. Developing NDT techniques

Hampton will continue to develop reliable methods of nondestructive testing to ensure safety and reliability of parts for the Army and also to implement features in parts that will be condicive to periodic nondestructive testing.

5.4. Involvement of engineering students in R&D activities

Hampton will continue to involve our engineering students intimately in state-of-the art manufacturing technologies, thereby supporting the next generation of highly skilled technologists.

Figures

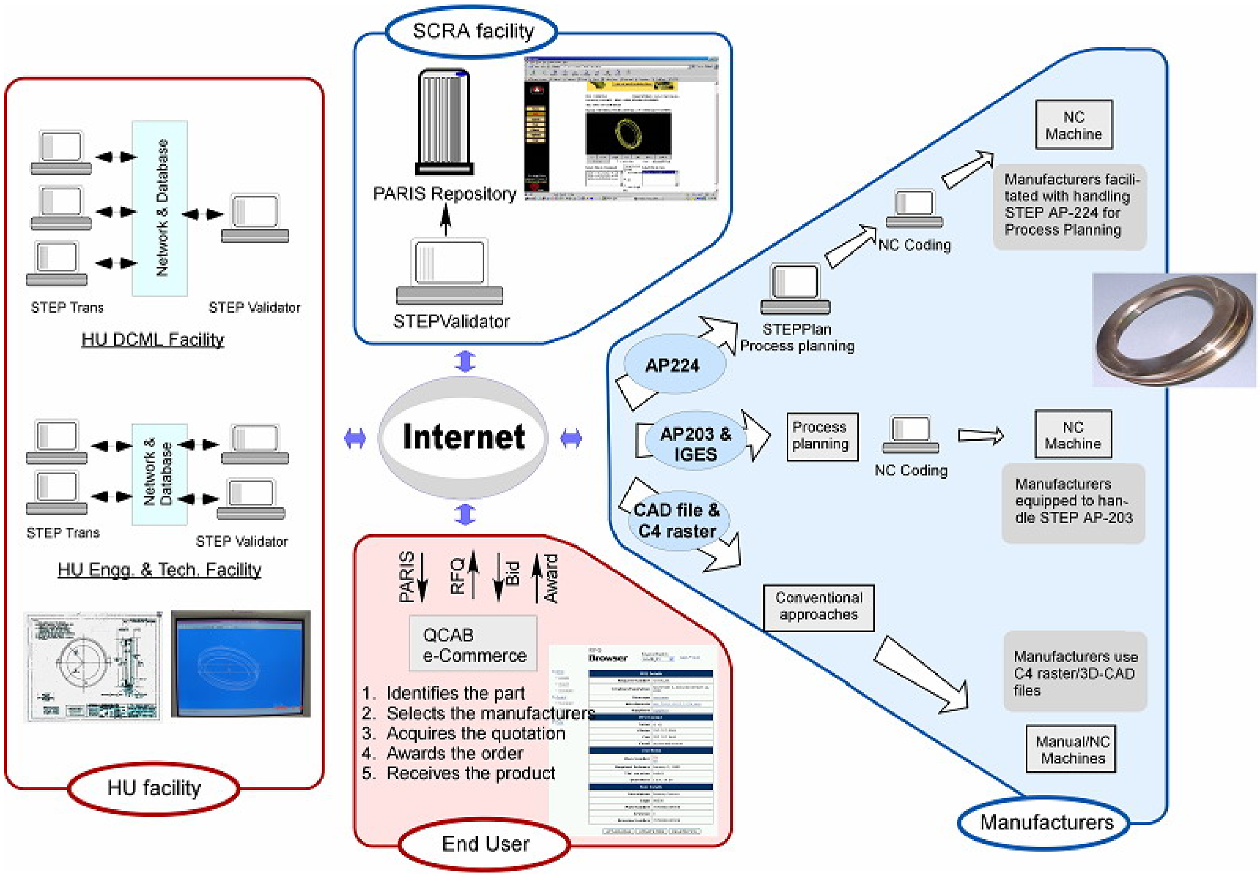


Figure 1 The VPERC process for the procurement of parts for the Army involves two stages: a) Reverse engineered product data are modeled in STEP at Hampton University and uploaded to a web-based server, b) End-users access the web-server, identify parts of interest to them, contact a set of manufacturers, acquire quotations and award the contract for manufacturing – all carried out via the Internet with no human intervention required.

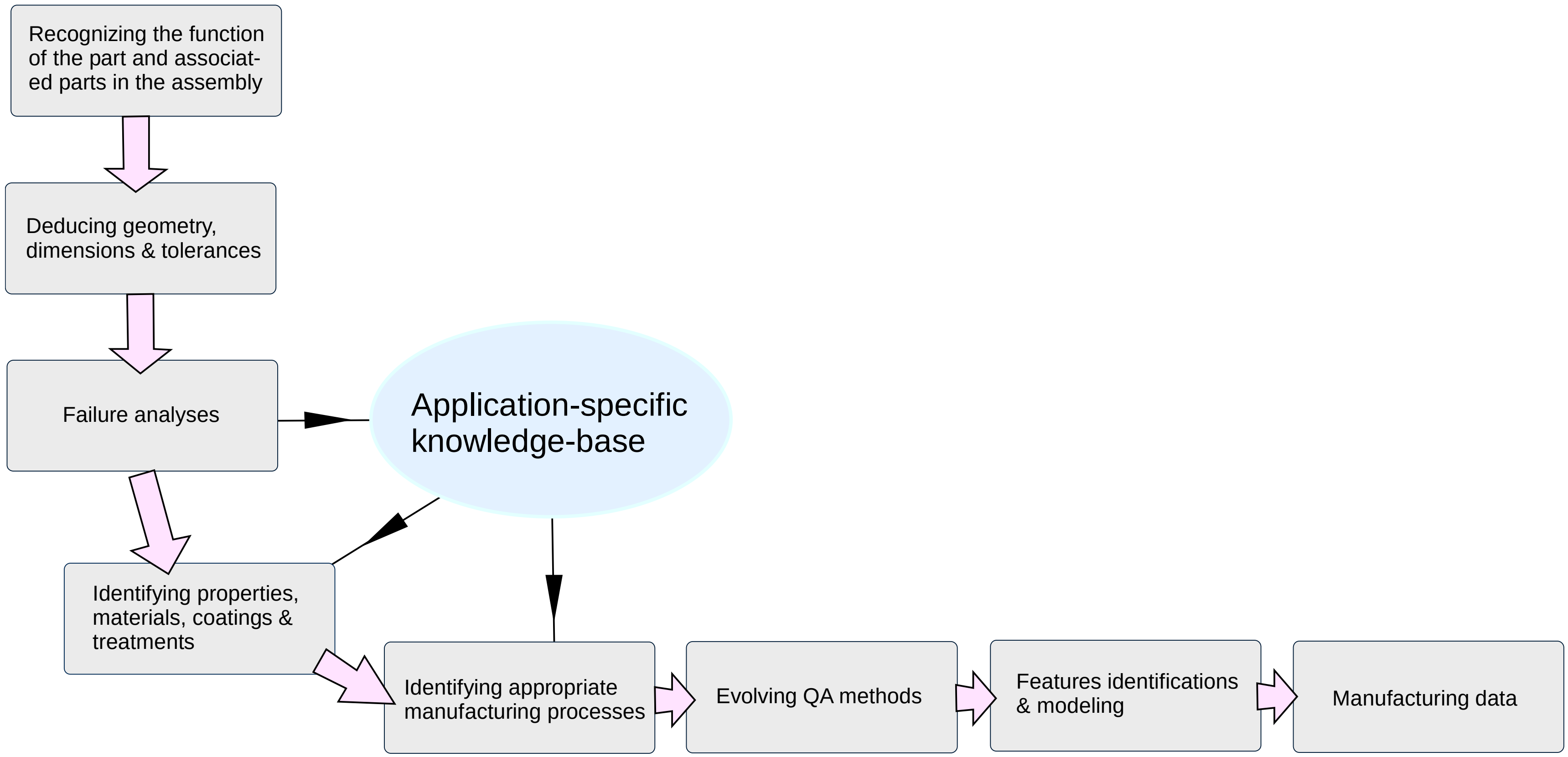


Figure 2 In most cases, reverse engineering involves routine processes of measuring dimensions, determining tolerances, and depicting geometry. Some parts may need detailed studies to deduce additional manufacturing data. Prematurely failed parts in critical structures should necessarily undergo failure analyses to determine causes and identify means of preventing premature failures in the future. The reverse engineering activities of the VPERC Lab expose our engineering students to advanced diagnostic and design techniques and call upon them to develop reengineering skills.

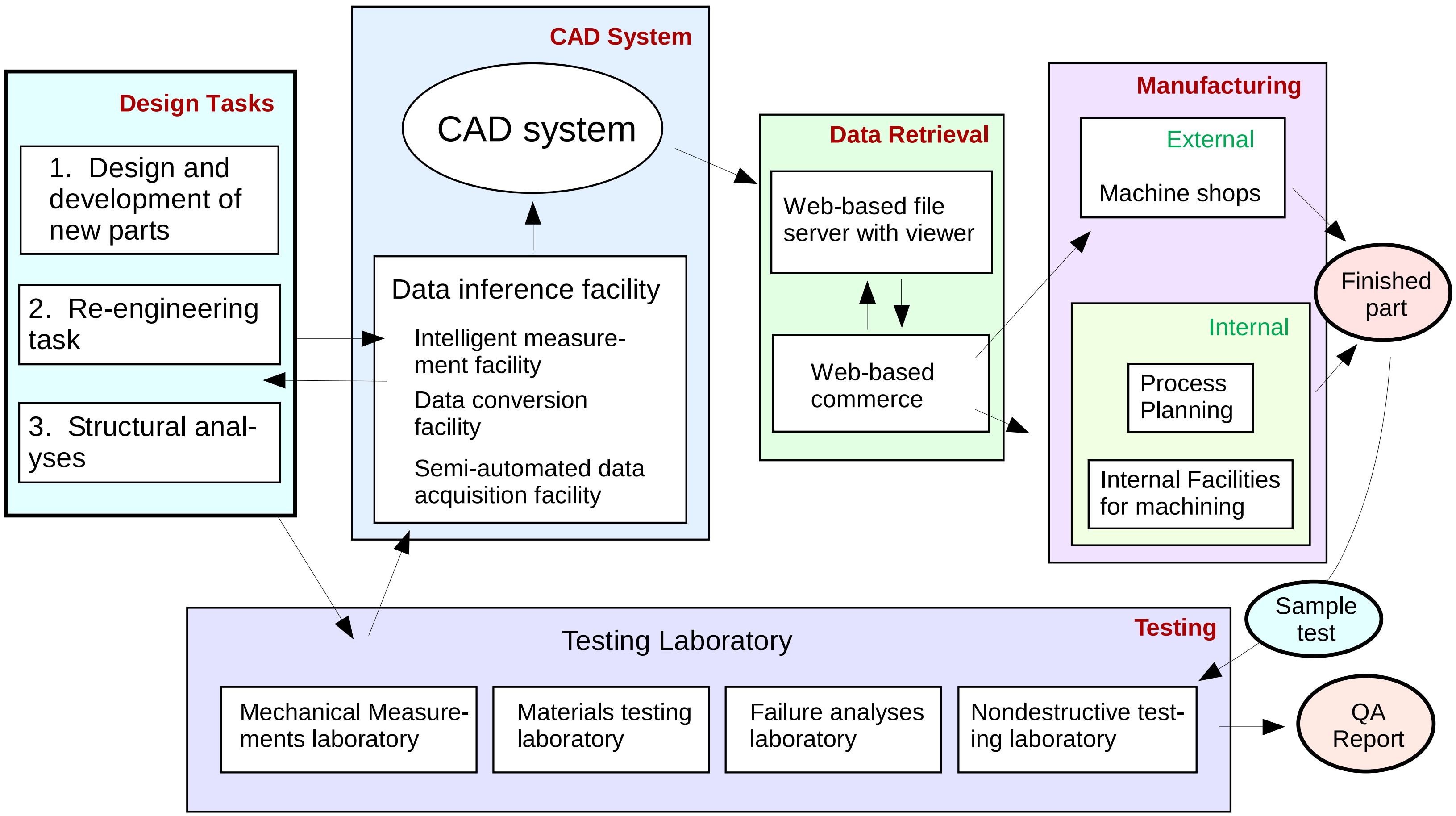


Figure 3 The VPERC laboratory was developed to handle the needs of reverse engineering and failure analysis. The facility is also used to develop more effective manufacturing methods and to address more contemporary demands.

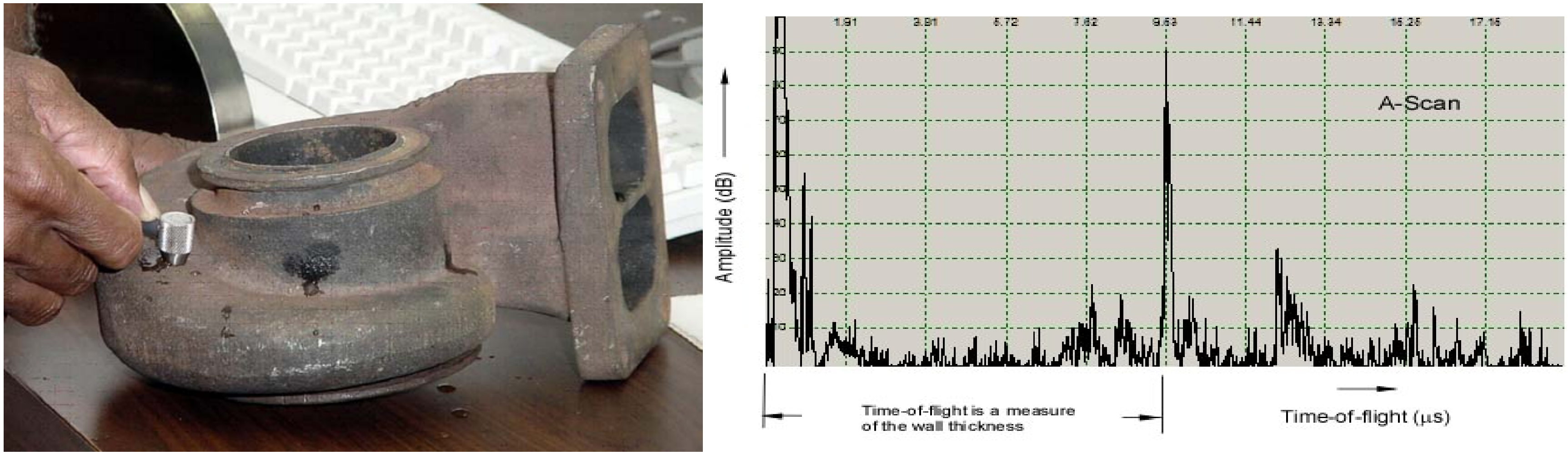


Figure 4 Ultrasonics is used in measuring the wall thickness of the part in inaccessible sections. Also, through ultrasonics, it is possible to compare the acoustic/elastic properties of materials which guide in identification of materials and structure.

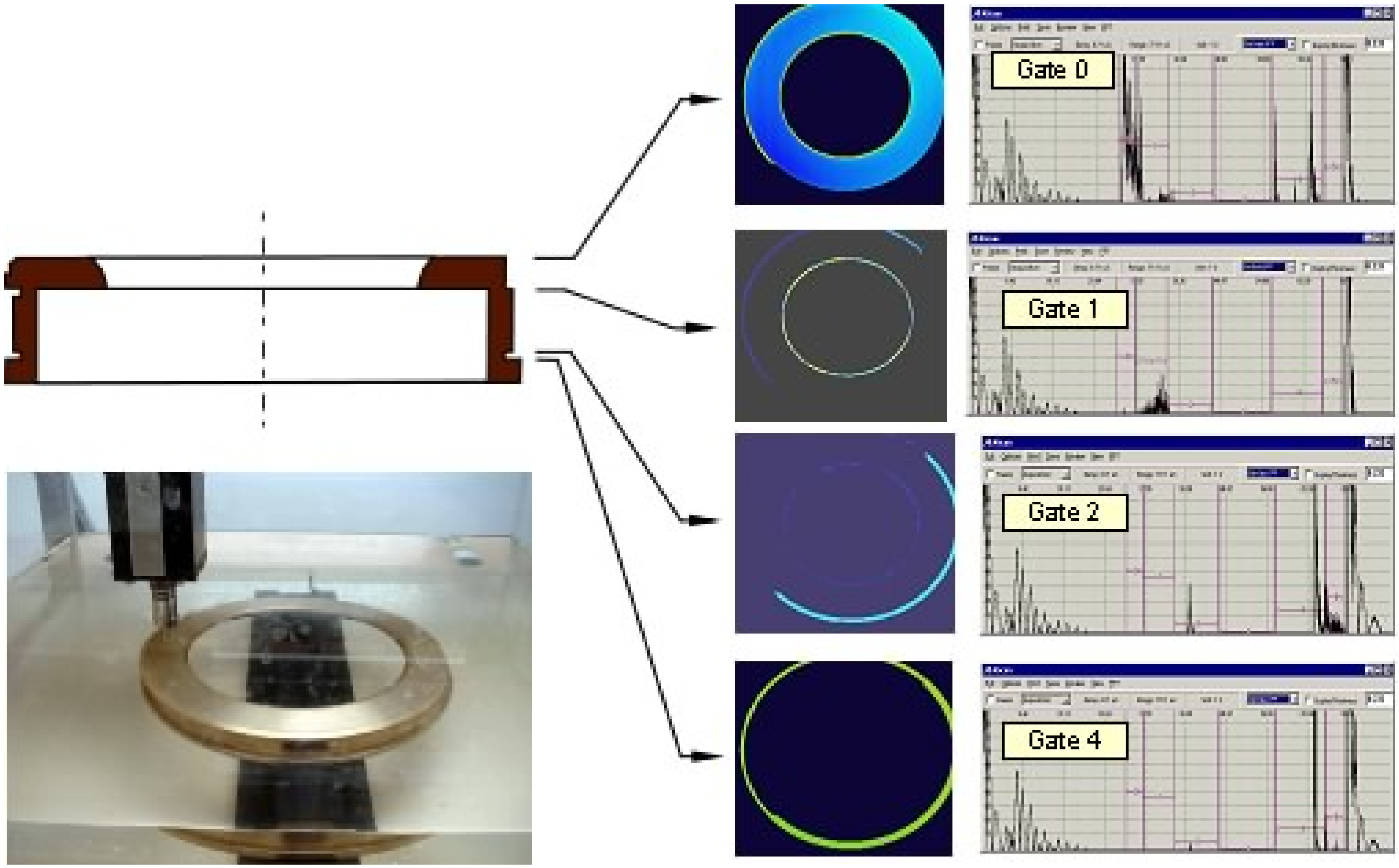


Figure 5 Ultrasonic testing is commonly used in materials testing and nondestructive testing. We use an ultrasonic scanner with an immersion tank to acquire geometry, dimensions and material characteristics in a single scan. A C-Scan image of a part is acquired at different depths as specified by the gate parameters in a single scan. Data from hidden regions, which in general are difficult to acquire by conventional methods, can be obtained more readily by ultrasonics. Furthermore, using ultrasonics, a parts assembly may be subjected to scan without the need to dismantle the assembly.

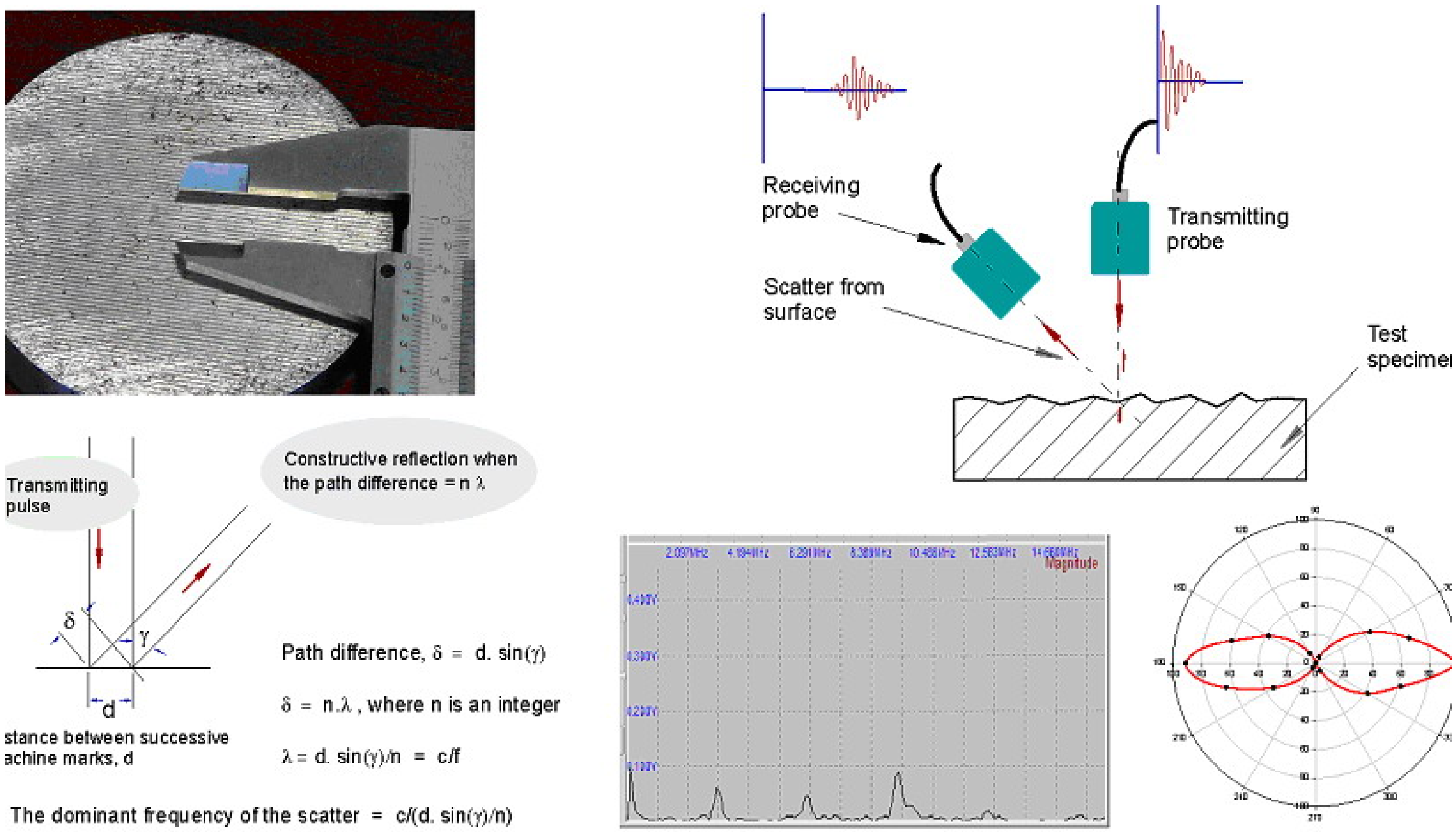
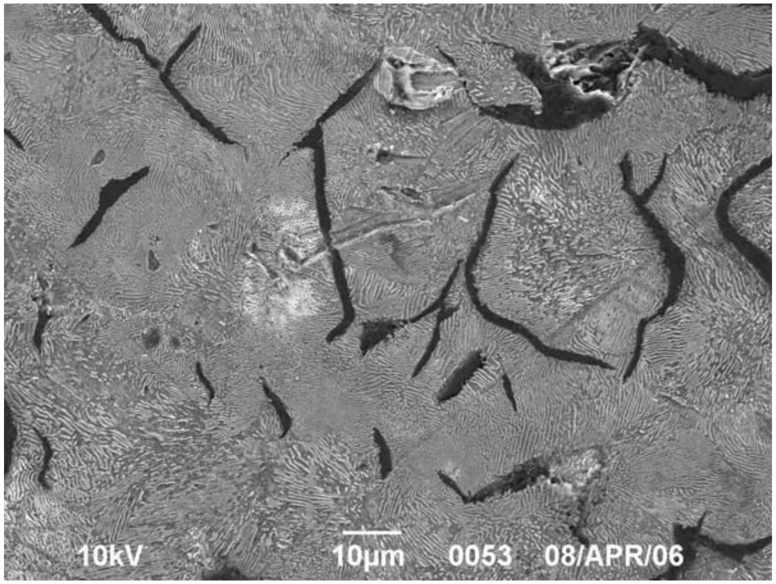
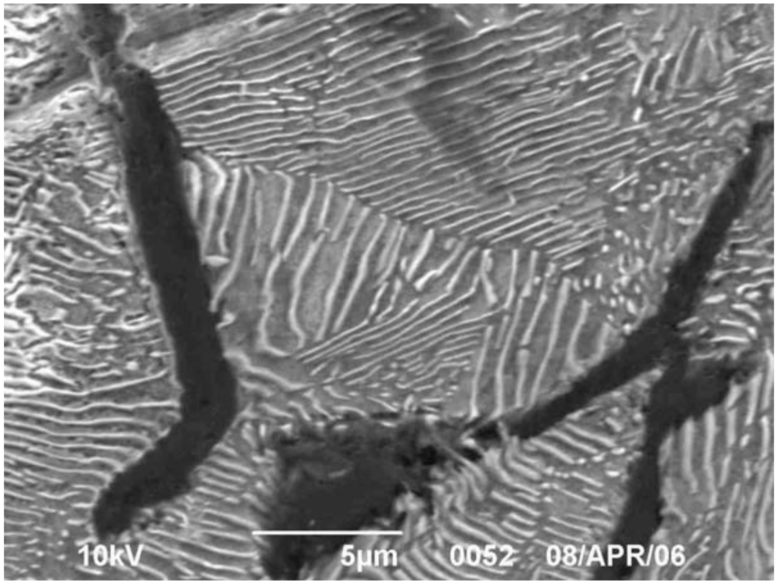


Figure 6 Ultrasonic scatter studies help in evaluating surface finish and the direction of machining marks. Orientation of the machining marks is detected very clearly. Finer finishes and non-uniform texture cannot be evaluated in the VPERC lab at the present time because of the limitations on the frequency response of the system. Application of dedicated instrumentation is expected to overcome some of the difficulties. Use of focusing probes that enable concentration of a beam onto a smaller region on the test sample is expected to improve the capability and results of the technique. The effort is expected to be useful in reverse engineering of mechanical parts with hidden details.

Figure 7 Students carry out research in ultrasonics and present their findings in conferences

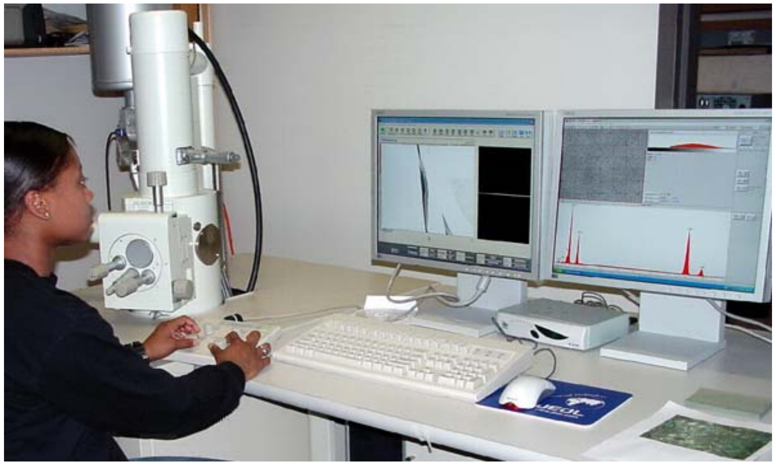
Figure 8 A Fused Deposition Modeling Unit is used by students to develop prototype parts





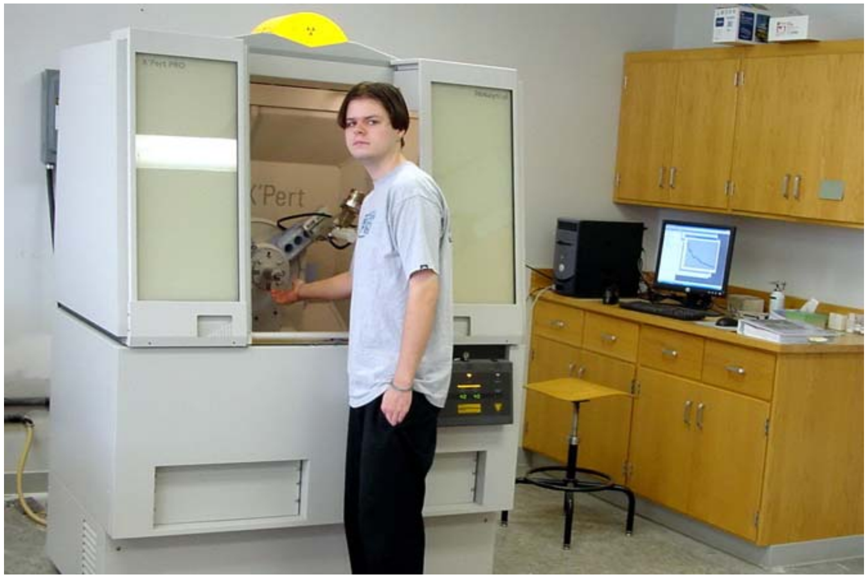
a) Scanning electron micrograph of casting reveals graphite flakes with pearlitic structure in cast iron structure

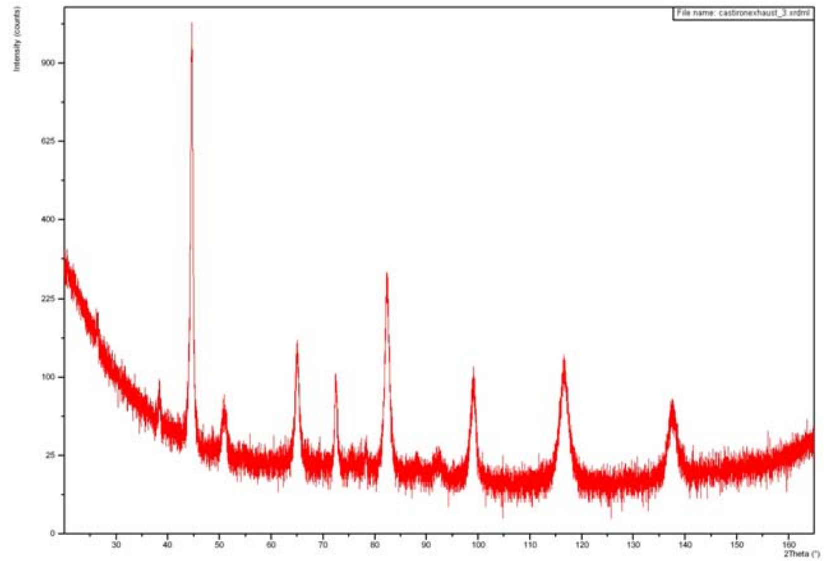
b) Same sample at higher magnification shows pearlitic layers clearly.



c) Scanning electron microscope with EDAX

Figure 9 Scanning electron microscope helps in studying metallic structure. The energy dispersive X-ray analysis (EDAX) accessory helps in identification of elements in each phase.

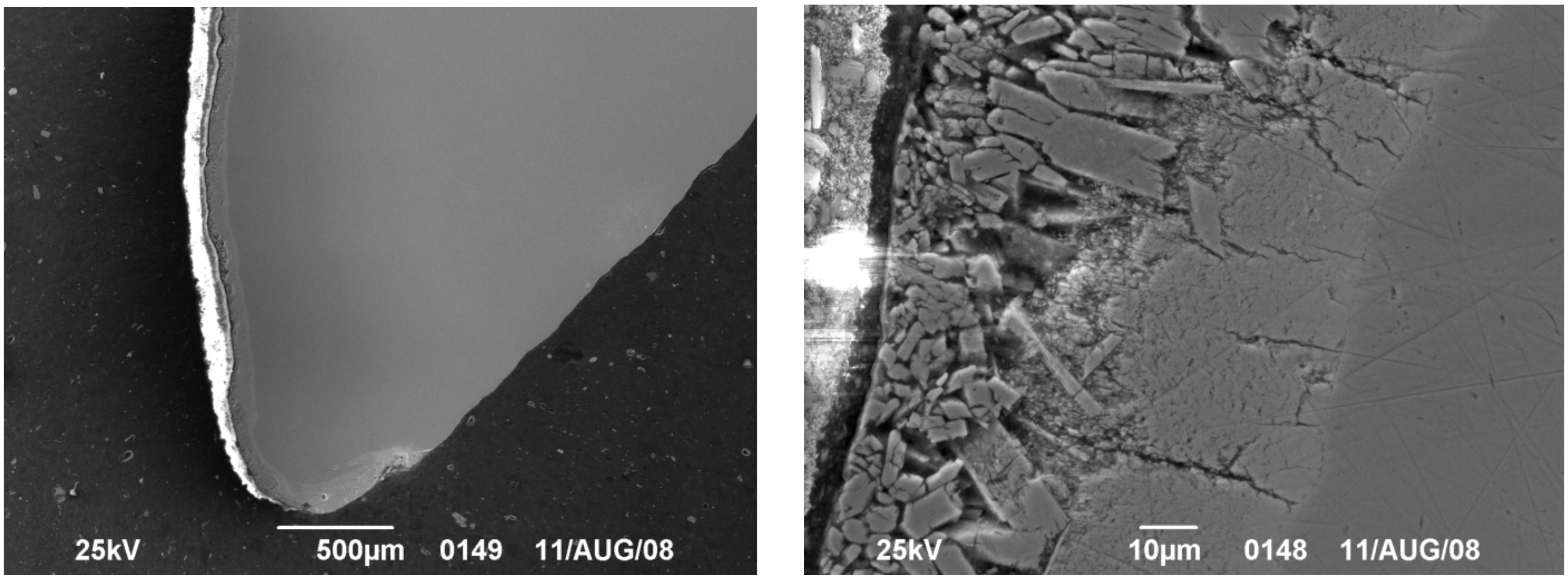




Photograph of the goniometer of the X-ray diffraction unit of Panalytical XPert Pro, MPD θ- θ system

Diffractogram of a powder sample from a reverse engineered part, in this case indicating BCC ferrite

Figure 10 X-ray diffraction studies are used to identify chemical composition and to measure residual stresses.



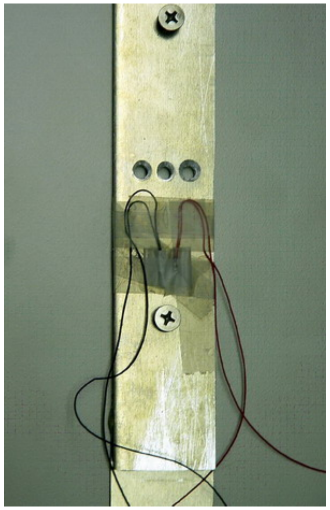
Figures 11 a) Microstructure of the sample from the shackle showing the coating thickness, b) Microstructure depicting the defragmented grains in the outer layers.

a) Original part with damage at the flange

b) Remanufactured part

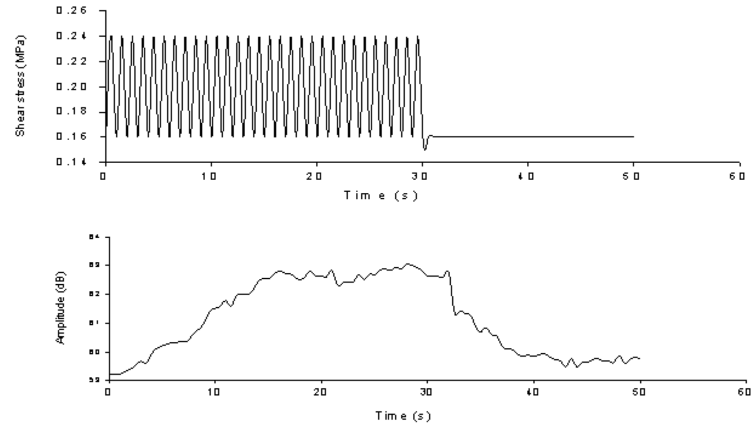
c) Stress distribution studies in the flange area showing stress due to the mounting fasteners

Figure 12 This case that houses an airspeed indicator gauge in the T38 aircraft has been reverse engineered and the part has been fabricated out of “Delrin” by machining. The original part was made by a molding process using thermosetting Bakelite. For remanufacturing the part in small quantities, machining has been identified as the most economical, yet effective, process.

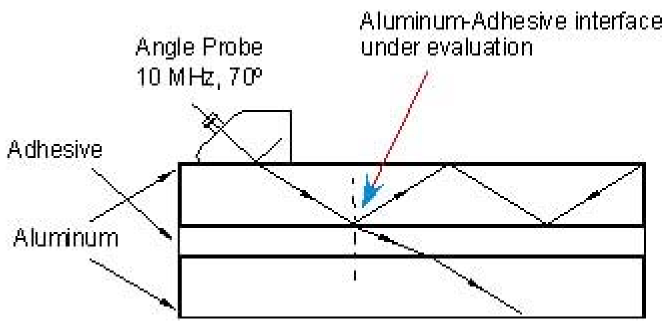


a)

b)



c)



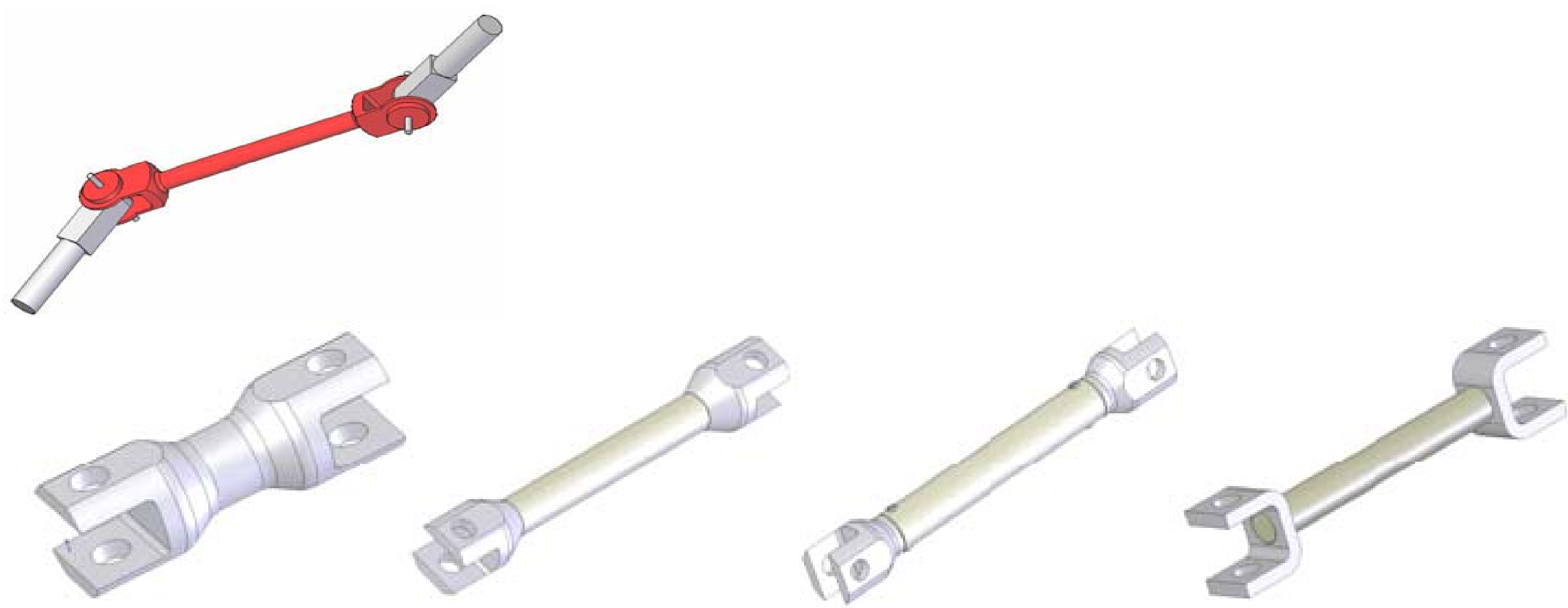
a) Cu RTD for in-situ temperature measurement

b) Tensile testing machine

c) Influence of stress on acoustic properties

d) Propagation of shear waves in test sample

Figure 13 Adhesive bonding is widely used in structural applications. Developing methods of assessing the integrity of the bond are very important to assure the reliability and safety of the part. Experiments have been carried out to understand the fundamental behavior of the adhesive layers when bond integrity is lost. Three areas that have been studied include the influence of external stresses, dynamic changes in temperature of the adhesives, and behavior of the bondline to acoustic waves.



a) Solid single b) Machined & welded c) Riveted d)Formed & welded

Figure 14 A link providing coupling in rotating machines is a commonly used engineering part. The R&D work studies the possibilities and pitfalls of fabricating the part with different manufacturing methods.

Figure 15. Photograph of the four sets of test samples generated by alternative manufacturing processes.

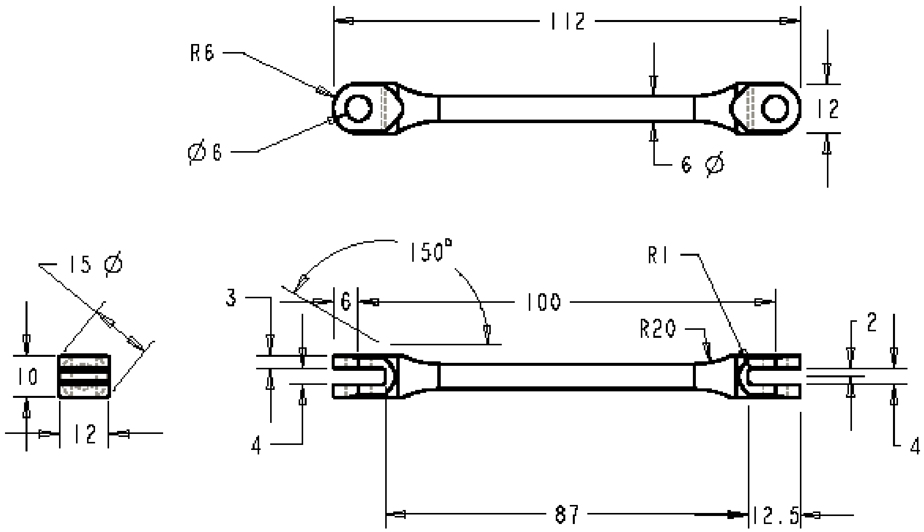


Figure 16a. Transmission rod test sample.

b. Photograph of the test sample.

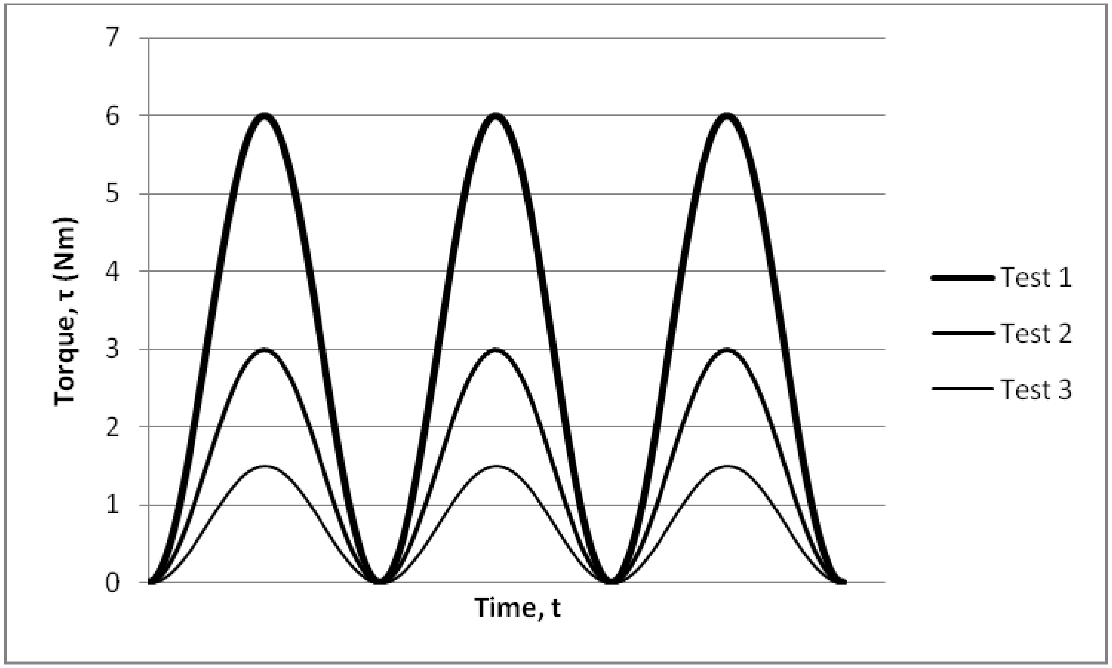


Figure 17 The test sample is subjected to three test conditions, ranging from 1.5 Nm to 6 Nm as the peak torque load.

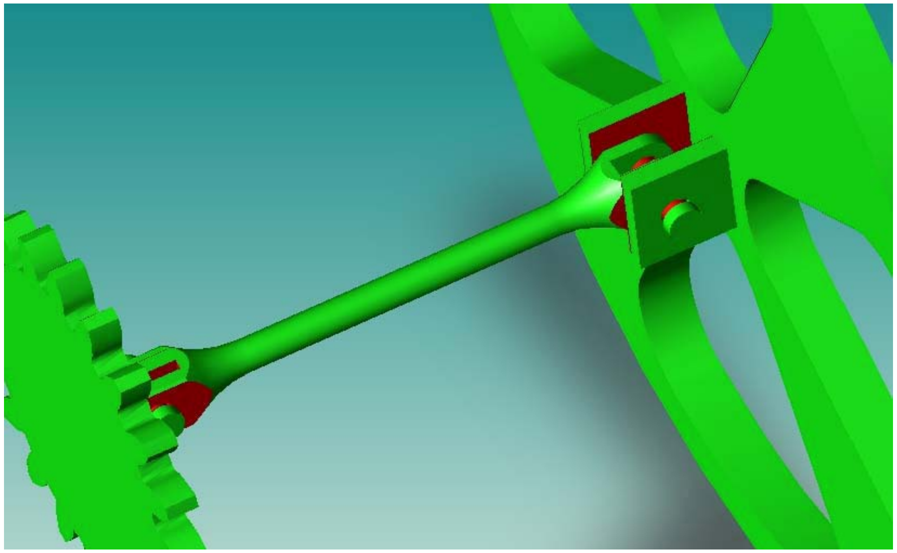


Figure 18. Assembly contact faces recognized from assembly model

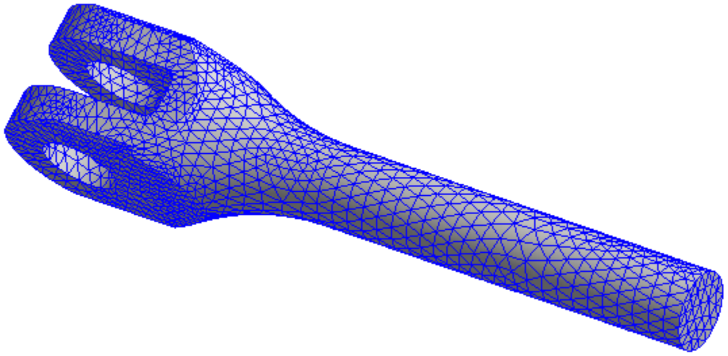


Figure 19. FEA model of the test sample used in stress analysis

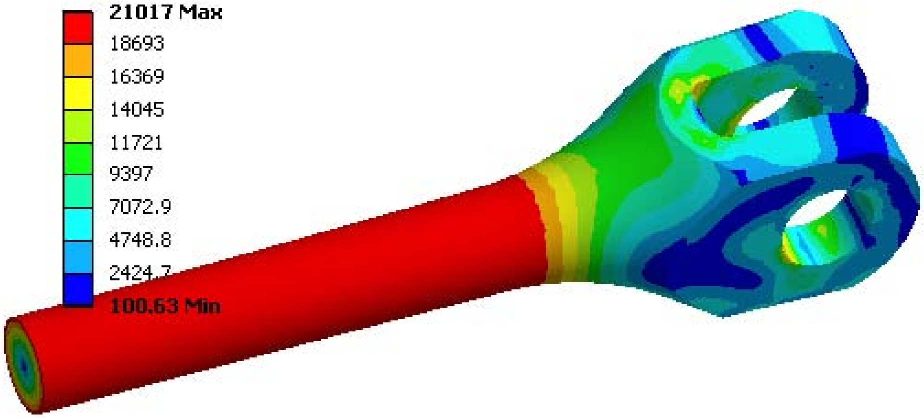


Figure 20. Maximum shear stress for Test 1

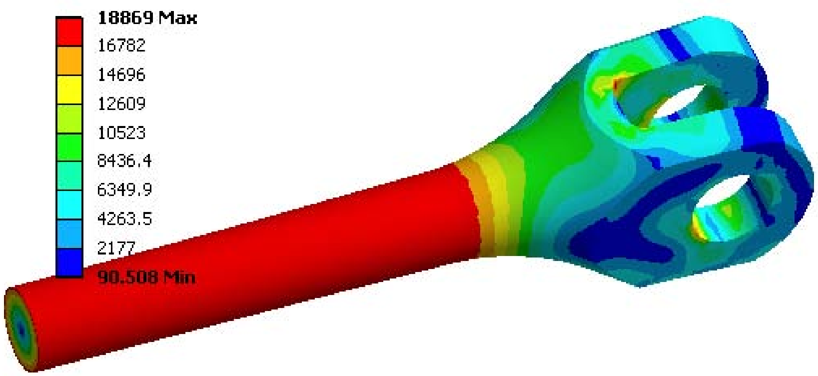


Figure 21. von Mises equivalent stress for Test 1

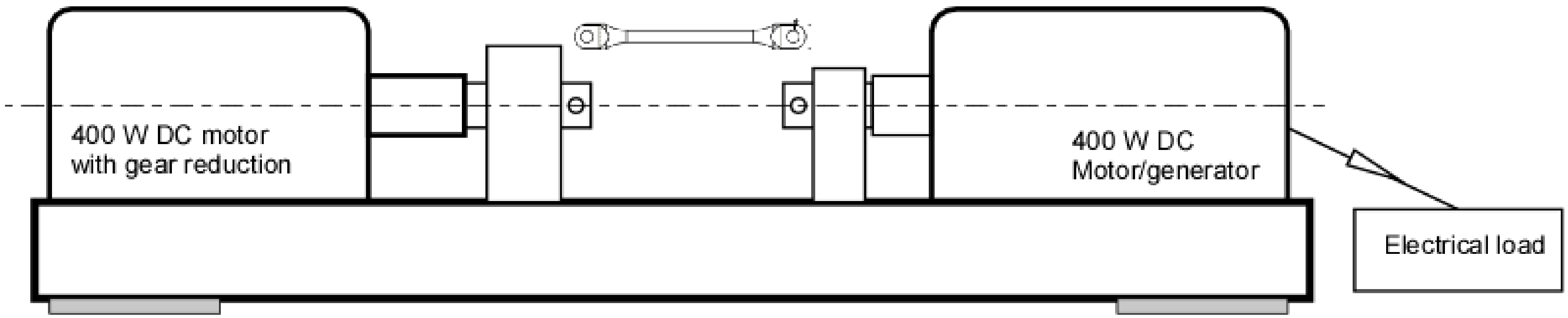


Figure 22. Experimental configuration proposed for testing fatigue strength of the test samples at differing torque levels.

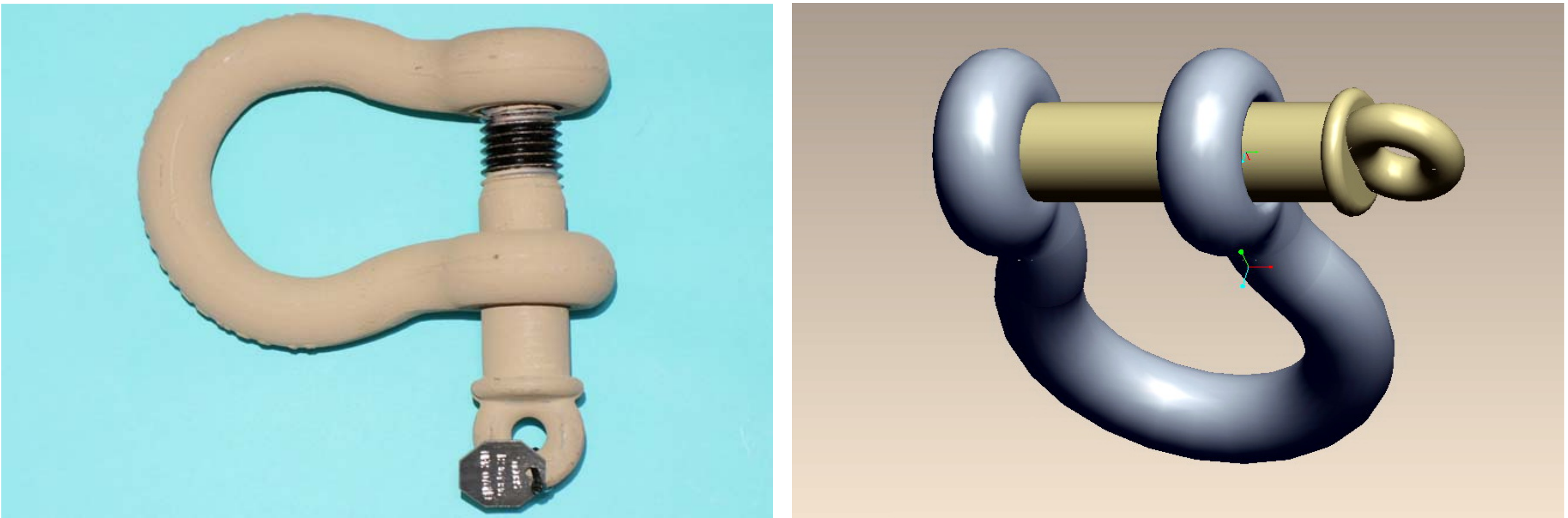


Figure 23. a) Photograph of the shackle b) CAD model of the shackle subjected to reverse engineering

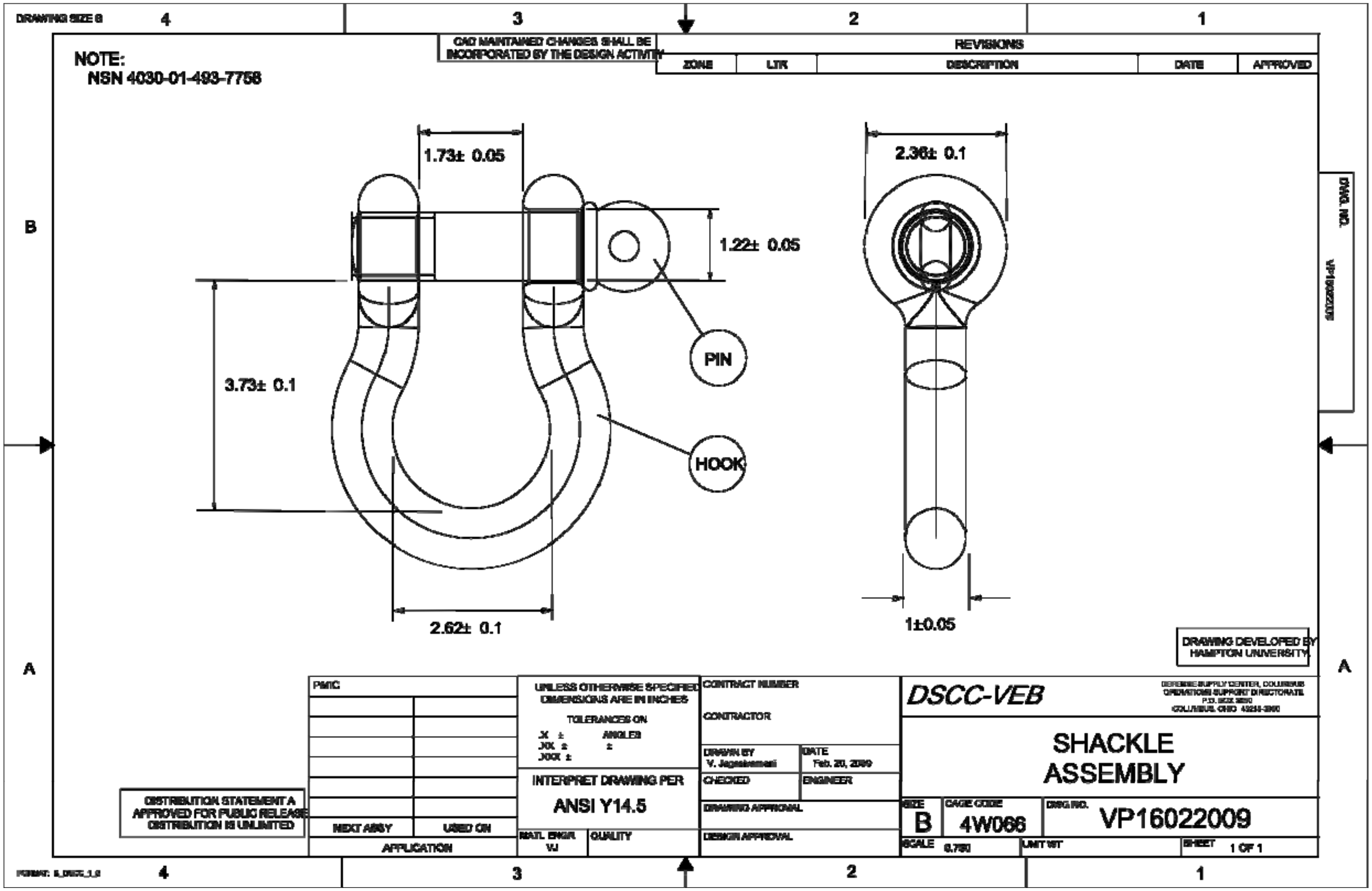


Figure 24. CAD drawings for the shackle for DSC, Columbus, OH.

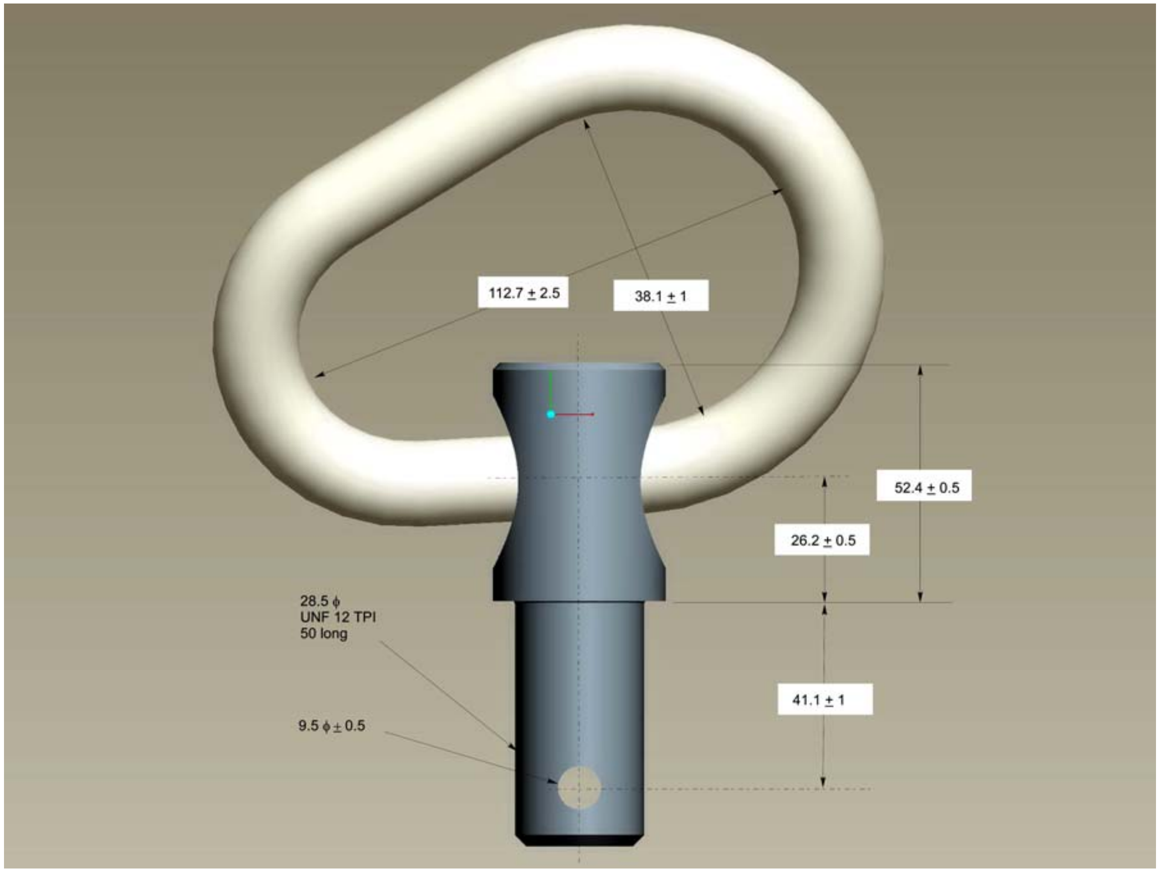


Figure 25. 3-D model of a swivel and hook assembly for DSC, Columbus, OH.

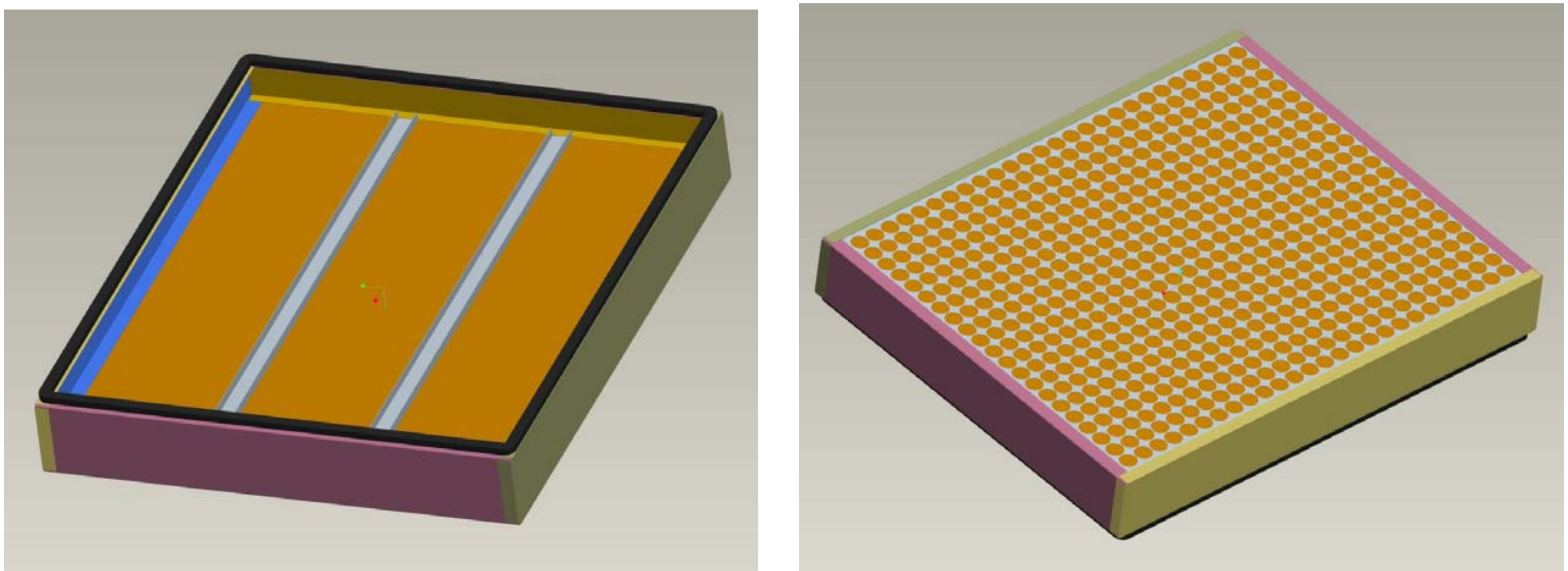


Figure 26. 3-D model of a filter assembly for DSC, Columbus, OH.

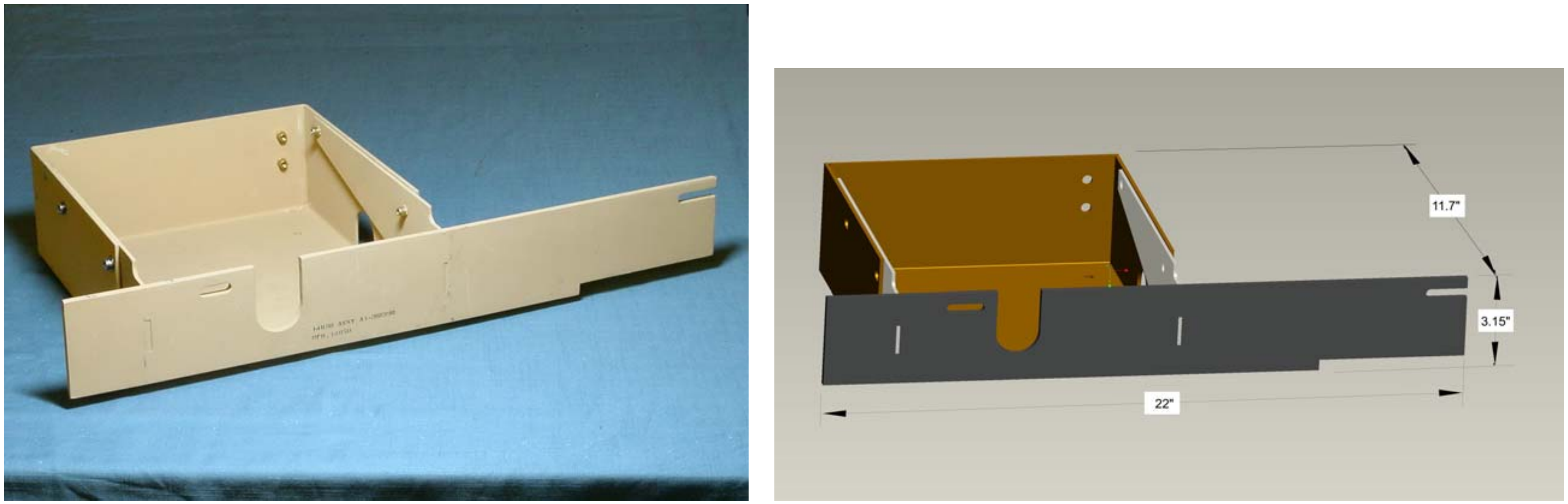


Figure 27 . Photograph and 3D model of an antenna bracket-mount. Technical data package prepared for the Tobyhanna Army Depot.

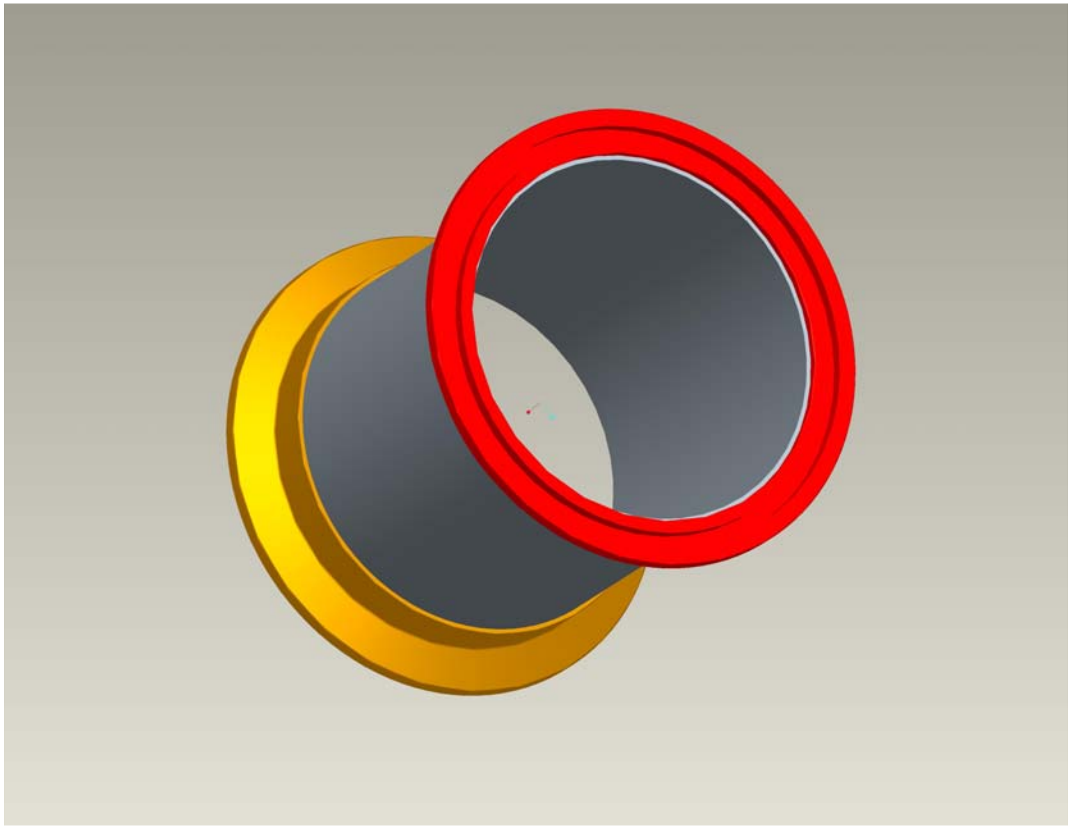


Figure 28. 3-D model of an air duct for DSC, Richmond, VA